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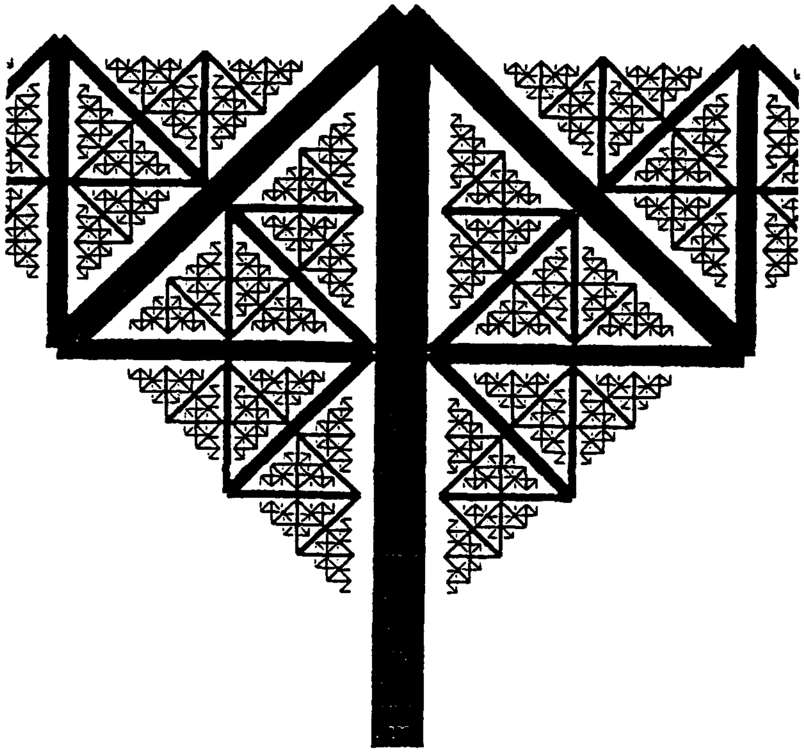

FIRST WORKSHOP ON SMART STRUCTURES

September 22-24, 1993

at

The University of Texas at Arlington

Sponsored by
Army Research Office

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ACTIVE AEROELASTIC TAILORING WITH ADVANCED MATERIALS

Terrence A. Weisshaar
Purdue University

Aeroelasticity - the interaction between structural deformation and aerodynamic loads - has a central role in the design of all lifting surfaces. Aeroelastic design requirements will translate into stiffness criteria imposed on the lifting surface structure to prevent phenomena such as flutter and divergence or to increase the lift on a flexible surface. Satisfying these criteria may create the need for additional mass that creates a weight penalty on the design. Advanced materials such as composites help to keep the weight penalty to minimum because they are lighter, stiffer and can be tailored to control the deformations found to cause flutter and divergence. New active materials such as piezoelectrics and shape memory alloys can actively control aeroelastic effects on demand, although their effectiveness is still unproven and concepts are still in their infancy. This talk will describe the history of aeroelastic tailoring with a special emphasis on recent efforts at active structural tailoring.

FUTURE ROTOR AERO-ACOUSTICS REQUIREMENTS

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The next generation of military rotorcraft is required to operate at much higher performance levels than in the past, particularly in the areas of nap-of-the earth, deep penetration operations, and air-to-air combat. These will require highly maneuverable, agile, and survivable rotorcraft, far exceeding the capabilities of those in the current inventory.

The single most important element of the rotorcraft for meeting these requirements is the rotor itself, since it is the primary source of lift, control, and speed. At the same time, the rotor is also a major source of acoustic radiation. Among the many factors affecting rotorcraft performance, the aerodynamic characteristics of the rotor is the most important, and is therefore the main subject of this paper.

The maneuvering capability of a rotorcraft can be improved by reducing or suppressing the vibratory loads on the rotor blades caused by aerodynamic separation and stall. This would have the effect of expanding the stall-limiting boundary of the rotor and thereby increase the available load factor in all flight regimes. The conventional way to obtain higher lift is to increase the blade area. However, this usually results in a heavier rotor that is also less efficient. With regard to compressibility effects and acoustic radiation, improvements have been obtained by sweeping, tapering, and thinning the tip region of the rotor blade. As a result, numerous families of airfoils and planform shapes have evolved that offer better advancing blade characteristics. However, improvements on the retreating blade side have not been as impressive.

The requirements for improved maneuverability and reduced susceptibility will clearly demand a substantial growth in the technologies for addressing rotor aerodynamics. Beside the passive blade design, new active blade control techniques, in particular using smart structures, must be considered and these must be accompanied by a more thorough physical understanding of these flow phenomena along with substantially improved prediction capabilities.

Various aerodynamic and acoustic requirements, often conflicting with each other, for new rotor capabilities will be discussed. The use of smart structures to the new generation rotor system is technically challenging, but has great potential.

ELECTRORHEOLOGICAL MATERIAL BASED ADAPTIVE STRUCTURES INCORPORATING IN-SITU SENSING AND NEURAL NETWORK REAL TIME CONTROL

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ABSTRACT

Intelligent material and smart structural systems are likely to have a dramatic impact on many defense related applications in the near future. Electrorheological materials are one of the primary types of controllable materials which make such systems possible. The current investigation was focused at the first time demonstration of ER material smart structures incorporating embedded vibration sensing and neural network based real-time control.

An ER material controllable structure based on the sandwich-beam configuration shown in Figure 1 was designed and fabricated. The adaptive beam was positioned horizontally with simply-supported end conditions and the controllable transverse vibration of the structure was studied. Excitation of the structure was realized through the usage of a non-contacting electromagnetic actuator positioned near the beam surface. The resultant motion at a point on the structure was monitored in real-time using both external displacement probe and internal polarimetric optical fiber sensors. Testing was performed over a frequency range of 0-300 Hz. with applied ER material electric field levels ranging from 0 kV/mm to 3.5 kV/mm. The displacement response observed at various field levels is shown as a function of frequency in Figure 2. From the Figure, the controllable vibrational response capability inherent to ER material adaptive structures is evident.

The resultant data obtained from vibrational testing of the adaptive structure was subsequently utilized to train a neural network. The goal of this process was to develop a neural network which could specify an electric field level for minimized vibration response at any excitation frequency. Given a sufficiently developed architecture, a backpropagation network should be able to develop a mapping of any function. However, it is not always easy to find this architecture. In the case at hand, the backpropagation alone performed miserably in mapping the one input/one output problem of frequency to 'optimal' voltage. For this reason a hybrid approach was developed using both backpropagation and the network architecture developed by Reilly, Cooper, and Elbaum (RCE network). For the RCE network, the input frequency was divided into classes based on the 'optimal' output voltage. This was done without any user input into the network. After this classification was performed, the class and the original frequency were fed into a new backpropagation network. This new network had very little trouble in obtaining a good mapping of the desired optimal electric field function, which is shown in Figure 3. In addition, this method was found to be insensitive to the architecture selected for the backpropagation network.

A closed-loop real-time control system based on this neural network was developed, and combined with the controllable structure and in-situ sensing system to yield a complete smart structure. The theoretically optimal displacement response performance

which could be realized using the control system is shown in Figure 4. The resultant structure was then tested while exposed to various excitation environments, and the ability of the sensing and control system to appropriately self-tune the embedded ER material properties to yield minimized structural vibrations was demonstrated.

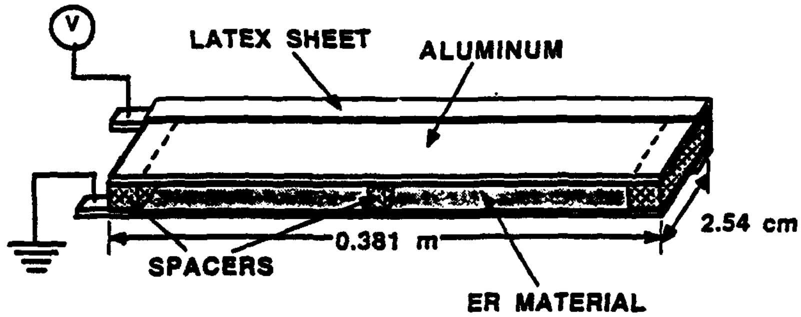

Figure 1: ER material adaptive beam configuration.

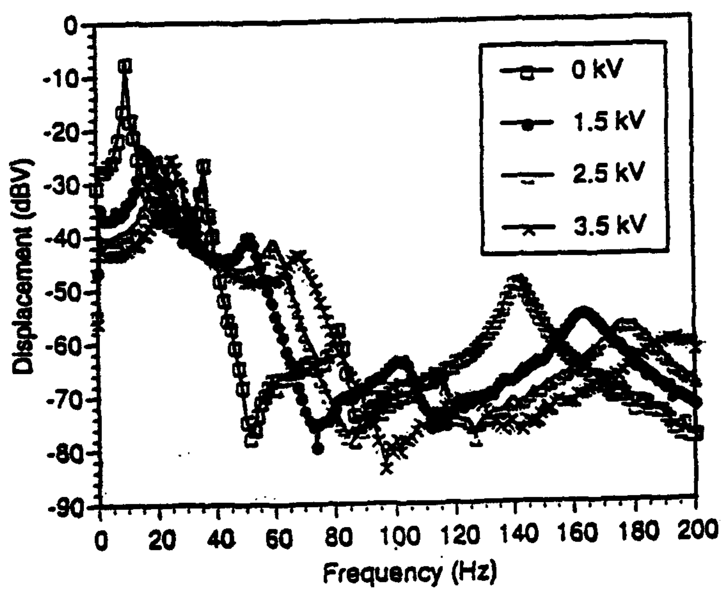

Figure 2: Controllable displacement response of ER material adaptive beam.

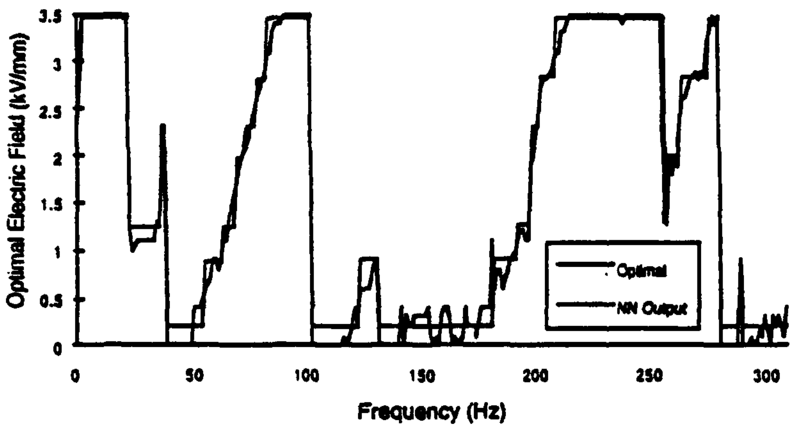

Figure 3: Optimal ER material electric field level (kV/mm) for minimized adaptive structure vibration response.

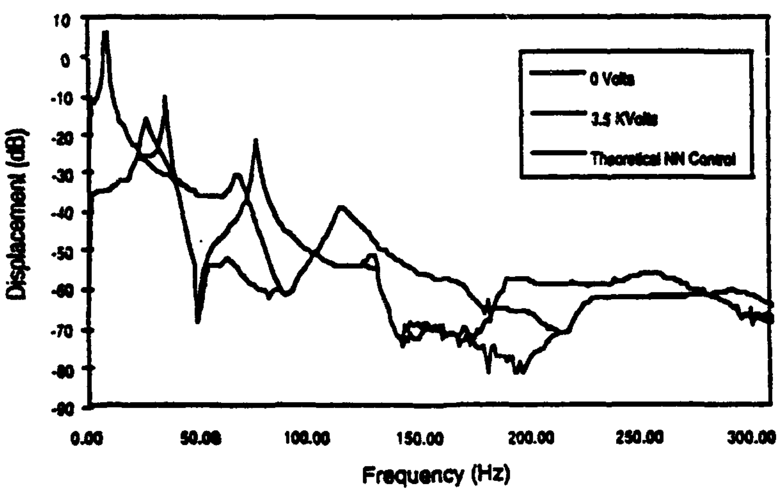

Figure 4: Uncontrolled experimental and theoretically optimal structural displacement response (shown in units of dBV)

Adaptive Control of Smart Structures Using Artificial Neural Networks

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Abstract

This paper details an integrated, interdisciplinary research program focused on designing and implementing intelligent controllers on smart structures. To demonstrate some of the capabilities of smart structures and to determine the limitations imposed by hardware realizations, we have designed and fabricated a simple cantilever beam and a three-mass test article incorporating flexible structures with NiTiNOL (SMA) actuators, strain gauge sensors, signal processing circuits and digital controllers.

A central goal of research in adaptive control in recent years has been to develop control algorithms for time-varying systems, nonlinear systems and systems with unknown parameters. These controllers have the ability to adjust controller gains for multiple operating points. The adaptive control techniques have been extensively employed for designing controllers for various industrial systems. One of the objectives of this paper is to investigate the applicabilities of adaptive control algorithms for smart structures. When the desired performance of an unknown plant with respect to an input signal can be specified in the form of a linear or a nonlinear differential equation, stable control can be achieved using Model Reference Adaptive Control (MRAC) techniques. The idea behind MRAC is to use the output error between the plant and some reference-model to adjust the controller parameters. There are two basic approaches to MRAC. When the controller parameters, $\theta(k)$, are directly adjusted to reduce some norm of the output error between the reference model and the plant, this is called direct control. In indirect control, the parameters of the plant are estimated as the elements of a vector $\hat{p}(k)$ at each instant k and the parameter vector $\theta(k)$ of the controller is chosen assuming that $\hat{p}(k)$ represents the true value of the plant parameter vector, p. Both the direct control and indirect control algorithms have been implemented on the smart structure resulting in perfect model following.

Having successfully implemented conventional MRAC techniques, the next logical step was to try to incorporate the MRAC techniques into a neural network based adaptive control system. The ability of multi-layered neural networks to approximate linear as well as nonlinear functions is well documented and have found extensive applications in the area of system identification and adaptive control. The noise rejection properties of neural networks makes them particularly useful in smart structures applications.

Adaptive control schemes require only limited *a priori* knowledge about the system to be controlled. The methodology also involves identification of the plant model followed by adaptation of the controller parameters based on the continuously updated plant model. These properties of adaptive control methods makes neural networks ideally suited both for the identification as well as the control aspects.

A major problem in implementing neural network based MRAC is translating the output error between the plant and the reference model to an error in the controller output which can then be used to update the neural controller weights. One recently proposed solution to this problem is based on a constrained iterative inversion of a neural model of the forward dynamics of the plant. This technique tries to predict the next output error and the next desired output error to calculate the necessary control signal at the next time instant. The algorithm has shown promise in that it offers a degree of robustness and generates a smooth control. It is from the iterative inversion process which the update method describe herein is derived. We use the neural identification model to find the instantaneous derivative of the unknown plant at one instant in time. The derivative is then used iteratively to search the input space of the system to find the input $u^*(k)$ which would have resulted in the correct system output. The control signal error $e_u(k) = u^*(k) - u(k)$ can then be used with static backpropogation algorithm to update the weights of the neural controller.

Having used artificial neural networks to implement MRAC algorithms, we propose to investigate the use of neural networks to identify a linear model of a system with the objective of adjusting the parameters of a linear controller based on the changes in the plant model. This method would be particularly useful when the parameters of the plant change considerably with changes in its operating condition. In this paper, three different techniques have been developed using neural networks for identifying models of structural systems from experimental data. First, a direct state variable model is obtained from the product of the weights of the neural network. Second, a technique for obtaining the coefficients of the difference equation model of the system has been developed. Third, an Eigensystem Realization Algorithm (ERA) has been augmented by a neural network method to generate the Markov parameters of the system. For smart structure applications, the size of such networks becomes very large. Therefore, we developed an adaptive neuron activation function and an accelerated adaptive learning rate algorithm which significantly reduces the learning time of a neural network. The models obtained by these identification techniques are compared to that obtained from the swept sinewave testing and curve fitting method. To reduce the order of the controller, the balance and truncation method was used to reduce the order of the model generated from the swept sinewave test. In this paper it has been shown that the model reference adaptive controllers can be designed and implemented on smart structure test articles using neural networks. It has also been shown that neural networks can be used for model identification for controller tuning in adaptive control problems.

Control Issues Related to Smart Structures

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There has been a recent surge of interest in the so-called "smart structure" where a l[illegible] number of active, light-weight, distributed sensors and actuators are bonded or embedded in the s[illegible] for the purpose of vibration suppression, shape control, and fault detection and mitigation.

Some key advantages offered by this class of input/output devices as compared with the more conventional devices are:

- sensor/actuator colocation simplifies controller design, and
- distributed sensors and actuators tend have better observability and controllability properties.

The reason that sensor/actuator colocation leads to simpler controller design is that structures are energy conserving or dissipating and the input and output maps are dual to each other. This property has been used extensively in the structure control community and lately for smart structures.

Colocated feedback is robust (as no model information is used) and can be implemented in a decentralized fashion. However, there may not be an unequal number of sensors and actuators (structures tend to be sensor-rich due to their simpler instrumentation requirements) and sensors and actuators may not be colocated. Furthermore, most of these actuators and sensors also contain severe nonlinearities and hysteresis, and they may age or become defective.

The goal of this paper is to consider the extension of our previous passivity based controller design to accommodate the idiosyncrasies of smart structures while still utilizing the inherent advantages that they offer. We will also present the addition of an outer feedforward loop to further augment performance without affecting the closed loop stability.

The nominally structure is described by the following linear equation of motion:

$$M\ddot{q} + D\dot{q} + Kq = Bu \tag{1}$$
$$y = C_1 q + C_2 \dot{q}. \tag{2}$$

If a static output feedback, $u = -G_1 y + v$, can be found such that the mapping from v to y is passive (since the system is linear time invariant, passivity is equivalent to positive realness), then any strictly passive feedback from y to $-v$ would render the closed loop input/output stable. If the system is also observable from y, then the internal state is also asymptotically stable. In terms of structure control, this approach is usually applicable when one has colocated sensors and actuators (though this is neither necessary nor sufficient). In the case of smart structures with piezoelectric sensors and actuators, it has been pointed out that a single piezoelectric patch can serve as both the sensor and actuator. If the patch is configured as a strain rate sensor, one then has natural colocation and a direct feedback can be used to achieve closed loop stability with virtually no model information. If the model uncertainty is considered, then as long as the uncertainty is also passive (and does not incur unstable pole/zero cancellation), the closed loop stability is not affected. In contrast to other methods such as H_∞ optimization, positive position feedback (PPF), linear quadratic Gaussian (LQG) controller, etc., the advantage of the passivity based approach is that it takes the phase of the uncertainty into account (unlike small gain type of approach where only the gain uncertainty is used), and it can be fine tuned within a well defined class, without affecting the closed loop stability, for

additional performance consideration such as sensitivity minimization, trajectory tracking, and disturbance rejection (in contrast to PPF, where gain tuning is essentially based on root locus of the nominal system).

However, the following additional issues need to be considered before successful application to smart structures can be assured:

1. Model non-idealities:
   (a) Excitation of unmodeled dynamics (e.g., torsional mode in a nominally bending motion).
   (b) Nonlinear effect (e.g., nonlinear voltage/strain relationship).
   (c) Hysteresis.
   (d) Creep.
   (e) Device aging.
2. Effect of discretization on rate feedback in a sample data system.
3. Effective utilization of model information to fine tune performance and robustness.
4. More sensors than actuators (nonpassive sensor/actuator pairs in general).

We now brief elaborate each of the above:

1. Linear model uncertainty, such as the unmodeled dynamics, can be considered within the framework of passive controller design through sensitivity minimization and limiting the feedback gain.

   Nonlinear model nonidealities can be addressed in several different ways:

   - Evaluate impact of the nonlinearities on the stability of the nominal linear closed loop system.
   - Explicit compensation of the nonlinearities, assuming that an accurate model can be found.
   - Explicit compensation and possibly controller reconfiguration with on-line model validity monitoring and model identification (especially for device aging).

   Dealing with nonlinearities in a smart structure is in the early stage, we will only present some preliminary thoughts in this paper.

2. In a typical sample data system, due to the zeroth-order hold (ZOH), the analog actuator waveform is a staircase function where the width of each step is the sampling interval of the system. When the sensor measures the strain rate and actuator imparts strain at approximately the same location, and if the sensor and actuator both have a wide bandwidth, the analog sensor output becomes a series of pulses. Sampling of these pulses in the A/D converter is extremely sensitive to the timing accuracy. As a result, the digitized sensor value would contain a large amount of error, rendering it useless. There are several approaches to deal with this issue:

   - Avoid the problem: apply analog feedback instead of digital feedback. However, the implied hardware constraint may not always be acceptable.
   - Arrange the sensor to measure the strain instead of the strain rate. For piezoelectric sensors, there may be a DC bias that needs to be calibrated.
   - Use a higher order hold device to render the input continuous. To ensure continuity, a one sample time delay needs to be incurred.
   - Avoid using the same device as sensor and actuator. If the sensor and actuator are separated, the dynamics of the physical system would serve as a filter to smooth the input staircase waveform.

   The first approach is implicitly used by authors who have advocated using the same piezoelectric patch as both a sensor and an actuator. We currently use the last approach in our laboratory and are working on the third approach.

3. When a nominal model is available, it can be used to minimize sensitivity and other performance related objectives in the context of passivity based feedback controller design. We have partially solved the sensitivity minimization problem by using a penalty function approach (to enforce the positive realness constraint on the controller). There is also the additional issue of controller order reduction while retaining the positive realness property.

4. When inputs and outputs do not form naturally passive pairs, we adopt the following approach:

   (a) Close the loops between naturally passive I/O pairs.

   (b) Synthesize passive pairs from the nonpassive ones.

   There are several possible approaches to synthesize a passive output from the physical output (for a given input):

   - Static Method: If there are more sensors than actuators, the sensors may be linearly combined to a smaller set of outputs as to render the system positive real.
   - Dynamic Method: A model sensitive method is to use an observer to reconstruct the state and then construct a new output which is positive real with respect to the input.
   - Adaptive Method: A possible improvement of the above method is to use an adaptive observer instead of a model based observer.

   The first two methods will be described in this paper. The last one is currently under development.

PROBLEMS OF ACTIVE CONTROL AND OPTIMIZATION OF COMPOSITE AND SANDWICH PANELS USING PIEZOELECTRIC STIFFENERS-ACTUATORS

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Application of piezoelectric materials as sensors and actuators represents one of the promising areas in research of smart materials and structures. In the present lecture we consider effects of piezoelectric actuators bonded to or embedded within composite or sandwich panels in the form of stripstiffeners. Such piezoelectric stiffeners can be used to control static and dynamic behavior of structures, and to arrest cracks.

The theory of active control of composite plates using piezoelectric stiffeners is developed for both geometrically linear and nonlinear problems. Applications of this theory to control of vibrations and dynamic instability are discussed. The feasibility of using piezoelectric stiffeners to reduce stress concentrations at the tips of cracks in composites is also illustrated. The latter problem is formulated using an elasticity solution of Sih based on the theoretical approach of Lekhnitskii.

Active control of sandwich panels is studied by assumption that the problem is geometrically linear. Design solutions considered include piezoelectric stiffeners embedded within the facings and either thin or shear deformable stiffeners bonded to the surface of the panel.

Design or control optimization of smart structures are also considered. In the lecture we discuss control optimization of orthotropic panel with piezoelectric stiffeners subjected to a central impulse. A voltage switch-over time is used as a control variable optimized to achieve motion reduction within the shortest time. The second optimization problem discussed in the

lecture is related to design of a panel with piezoelectric stiffeners subjected to an uncertain impulse. The impulse is modeled by initial velocities represented by double Fourier series with the amplitudes that include deterministic and uncertain components. The worst possible impulse is determined using the method of Lagrange multipliers. The solution can be combined with a design optimization problem.

In the problems considered in the lecture, stiffeners are usually designed in pairs, the components of each pair being symmetric about the middle surface. The advantage of such an approach is that it provides a designer with a degree of flexibility. In the case of a transverse deformation, out-of-phase voltage applied to piezoelectric elements on the opposite sides of the middle surface yields bending moments that are more effective for control than in-surface stress resultants. On the other hand, in the problems of in-plane stresses control, as, for example, in the case of cracks in composites, in-phase voltage applied to the elements on the opposite sides of the middle surface generates in-plane stress resultants that are more effective than stress couples.

Experimental Investigation into Damage Detection Using Artificial Neural Networks

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An essential part of the intelligent material systems concept is the ability of structural systems to sense and monitor their health. Providing structures with this ability will lead to a more energy-efficient and safer design. Health monitoring can be done by an array of sensors which continuously monitor the stress level during the structures's use; or, the structure can be periodically excited and effective interpretation of the vibration signature obtained from a limited number of sensors can be used to identify changes and possible damage. Analytical/finite element models of the structure are often used for relating the changes in the vibration signature to damage location and size. In contrast, this study presents an attempt to use neural networks with purely experimental data as its input in order to quantitatively and/or qualitatively detect a delamination between a composite patch and an aluminum beam. This specimen geometry was chosen because it is representative of a repair technology being investigated for aging civil engineering and aerospace structures. For the success of this repair technique, the integrity of the bond between the high-strength composite and the base structure must be assured, and this investigation seeks to address this.

The specimen consists of an aluminum beam with a composite patch bonded to it; various specimens were made with different sized delaminations in the patch/beam bond (see Fig. 1 and Table I). The frequency response data is obtained using a piezoelectric patch bonded to the beam on one side of the patch acting as an actuator and another piezoelectric patch bonded on the other side of the patch acting as a sensor. The frequency response data in the range of 500 to 1750 Hz with an increment of 6.25 Hz, was used to train the neural network simulation code contained in the Matlab Toolbox. The magnitude and phase angle data wwere patched together into a single column vector for input to the network. The output layer for each of the different networks that were tested consisted of a single output neurode that could give an output corresponding to the state of the patch. Two types of tests were performed: qualitative testing and quantitative testing. For the qualitative tests, the desired output of the single neurode was either 1 or 0, where 1 represents a fully laminated patch and 0 represents any size delamination. Conversely, for the quantitative tests, the desired output was a value between 1 and 0 corresponding to the fraction of laminated patch surface. For the qualitative tests, a two-layer network with 15 hidden-layer neurodes and logarithmic sigmoid transfer functions in every layer was chosen due to its consistent convergence. Examination of the results for this test (see Fig. 2) show that the network performed fairly well when the training set was inclusive and the delamination was one inch or greater. These results are promising in that the network can give a general indication of damage or no damage even on untrained specimens. For the quantitative tests, a three-layer network with 24 neurodes in both the first and second hidden layers was chosen for its ability to converge. Additionally, log-sigmoid transfer functions were used in the input and hidden-layer neurodes but the linear transfer function was used in the output layer neurode. This combination of transfer functions is tailored to approximate any non-linear function. As opposed to the 0-1 output, the desired output in this case was the fractional amount

of laminated surface between the patch and the beam. The network performed better in that it was able to determine an approximate level of delamination even with moderately representative training data (see Fig. 3).

This initial study has shown promising results, and the work is being continued with plates.

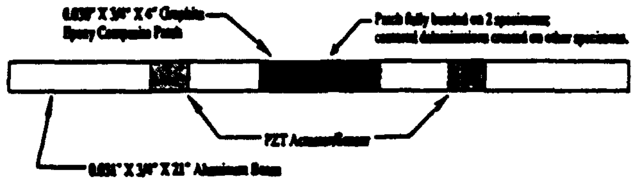

Fig. 1 Typical experimental beam specimen.

Table I Test specimen nomenclature

Label	L1(a,b)	L2(a,b)	D1	D2	D3(a,b)	D4(a,b)	D5	D6	D7	D8	D9
Description	Fully Laminated (Beam # 1)	Fully Laminated (Beam # 2)	1/2" Delamination	1" Delamination	2" Delamination (Beam # 1)	2" Delamination (Beam # 2)	3" Delamination	1/2" Delamination*	3/4" Delamination*	1" Delamination*	1.5" Delamination*
Qualitative output	1	1	0	0	0	0	0	0	0	0	0
Quantitative output	1	1	0.875	0.75	0.5	0.5	0.25	0.875	0.813	0.75	0.625

* delaminations created by slicing bond on beam L2

(a) and (b) refer to two separate sets of FRF data for the same beam specimen

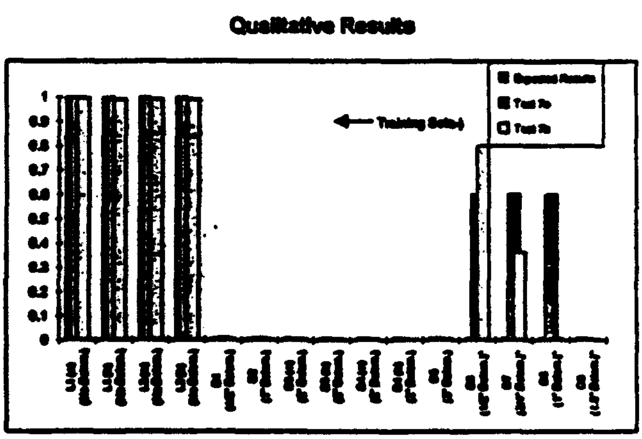

Fig. 2 Qualitative results obtained from the ANN.

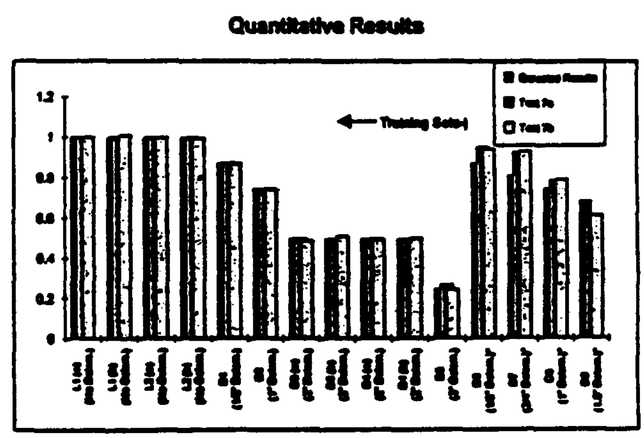

Fig. 3 Quantitative results obtained from the ANN.

INDUCTIVE LEARNING METHODS FOR DAMAGE IDENTIFICATION AND MITIGATION

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We are investigating the use of inductive learning methods (learning from examples for both damage identification and subsequent mitigation of the effects of damage. The potential advantage of these methods is the lack of dependence on analytical models of the structural system and the ability to learn on-line.

Our approach to the research is to use available inductive learning tools and specialize them for the tasks we are performing. This specialization and the choice of the tools is the heart of the research. For each tool we investigate modifications or choices in three areas; the input, the processing, and the output. The input is modified by selecting the kinds of data and by processing the data to present it in usable forms. The inductive learning tools are modified by adjusting available significance factors, by adjusting the performance indices, and, whenever possible, adjusting the processing algorithms. The output of the tools are usually in the form of rules, these rules are modified to make them more understandable and usable.

Simulations and experiments with the "Boxes" inductive learning tool of Michie and Chambers have been conducted to produce dynamic control of vibration levels in test systems are a precursor to control of damage effects. Both transient and forced vibration control have been investigated with a variety of performance measures, control and state quantizations, and learning methods without the need for modelling of the analytical or physical systems being controlled.

Experiments with the commercial inductive learning tool KnowledgeSeeker have been conducted to identify damage in composite plates and in aluminum plates. Dynamic inputs utilized have been: single frequency, and broadband. Dynamic data has been taken with accelerometers, strain gages, and a laser system. The learning tool has been adjusted to produce a wide range of rules for distinguishing the presence of damage and modifications in the test structures.

Inductive learning methods have been shown to have utility for the dual tasks of damage identification and damage control in structures.

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* Associate Professor, † Graduate Research Assistant

FIRST ARO WORKSHOP ON SMART STRUCTURES & MATERIALS
University of Texas at Arlington

September 22-24, 1993

DAMAGE DETECTION IN COMPOSITE STRUCTURES USING PIEZOELECTRIC MATERIALS

by

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ABSTRACT

This research consists of an experimental program for damage assessment in composite structures. All load carrying members of structures continuously accumulate damage in their service environment. In order to ensure safe operating conditions, it is necessary to monitor the damage continuously and to take temporary corrective actions by redistributing the load to minimize the effects of such damage until the structure can be repaired.

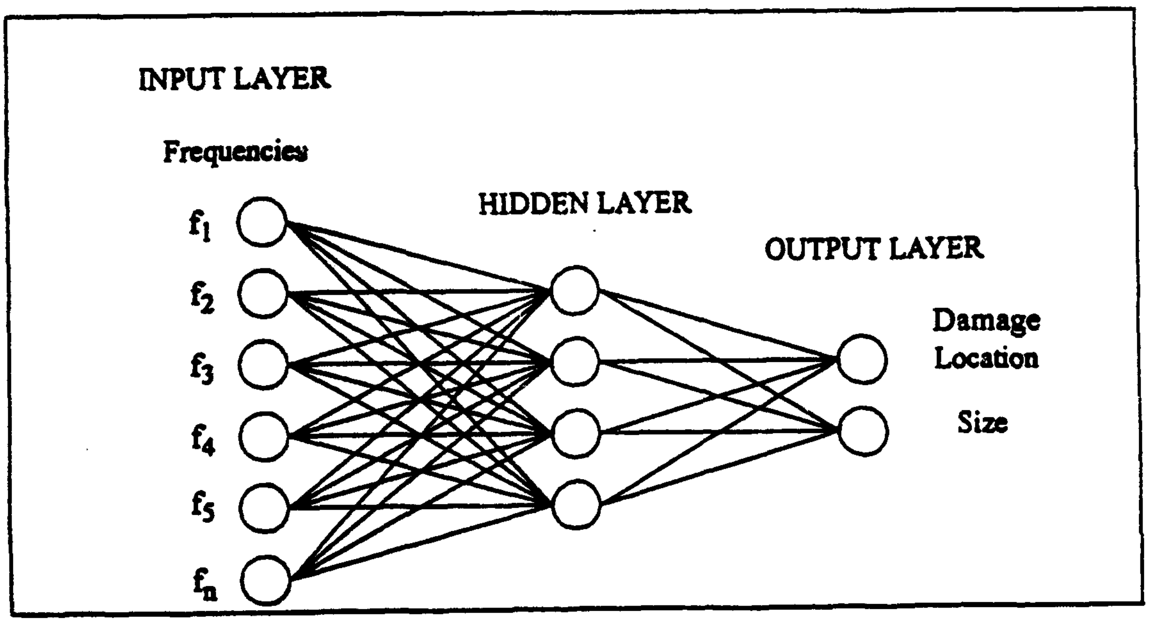
The consequences of all damage in composite structures are changes in stiffness, strength, and fatigue properties. Measurement of the strength or fatigue properties during the damage development is not feasible because both of them require destructive testing. However, stiffness can be measured frequently during damage development because damage directly effects the dynamic response of the structure. In fiber-reinforced composites a state of damage can be detected by a reduction of dynamic stiffness and an increase in damping, whether this damage is localized or distributed throughout the specimen. This change in stiffness results in a decrease of the natural frequencies of the specimen. Also, since stress distribution throughout a vibrating structure is nonuniform and is different for each natural frequency (mode), any localized damage would effect each mode differently depending on the particular location of the damage. The measurement of natural frequencies of a structure at two or more stages of its life therefore offers the possibility of detecting the presence of damage and locating its position.

In this research, damage in composite structures is being detected by embedding piezoceramic sensors. Modal analysis is carried out using piezoceramic patches as both sensor

and actuator on structure members. Using piezoceramic actuators, the member is excited at different sinusoidal frequencies, and, using piezoceramic sensors, the response of the member is measured. The advantage of using active materials for system identification is that the condition of the structure can be continuously monitored, and by using an integrated microprocessor, the sensor output can be continuously evaluated.

Two models are used in this research. A finite element model of a delaminated a composite beam with embedded piezoceramic patches has been derived. The frequency response data from this derived model is compared with the experimental data and with data generated from a similar model developed in the ABAQUS finite element package. In ABAQUS, the delamination is modelled as two beams, made of solid elements, above and below the plane of delamination. Spring elements are used to connect the beams in the un-delaminated region and gap elements are used to connect the beams in the delaminated region.

A back-propagation neural network code has been written and is being trained with the frequencies of the first ten modes obtained from modal analysis data from piezoceramic sensors in both damaged and healthy composite beams. The effectiveness of neural networks in determining the location and size of any delamination is discussed.



Neural Network for Damage Detection

MEANINGFUL DAMAGE EVOLUTION TRACKING IN COMPOSITES USING STRUCTURALLY EMBEDDED OPTICAL FIBER SENSORS

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One does not have to examine the "Smart Structures" literature very deeply to locate references to optical fiber sensors that are embedded in composite materials to *measure stress, strain, and temperature*. Most every attempt at this type of arrangement follows the philosophy that the sensor is the contribution to the field, and not the measurements. As a result, one quite often finds optical fiber sensor data that can not be related directly (or otherwise) to the thermomechanical measurand of interests. It is in fact much easier to obtain signals from embedded optical fiber sensors (and virtually all other embedded sensor types for that matter) than it is to interpret them. This paper examines the optomechanical experimental/analytical/numerical hybrization required to 1) identify meaningful measurands that are related to internal damage, and that are capable of being measured, 2) design optical fiber sensor systems that are capable of making said measurements, and 3) develop relationships between the measurements and the damage evolution in the host material system. The examination motivates two optically and mechanistically sound philosophies of using optical fiber sensors for health monitoring of composite material systems. This paper outlines these two philosophies, presents the development of the requisite analytical models and optical fiber sensors required to implement them.

The distinguishing feature of this research is that we treat the "fiber optic smart structure" as a thermomechanical system, and let the damaged mechanics define the sensor requirements and not vice-versa. The end goal is to uniquely infer internal damage descriptors from the measured optical signals.

Stress concentration reduction in a plate with a hole using piezoceramic layers

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ABSTRACT

Actuation in plates can be achieved by applying an electric field on embedded or surface mounted piezoelectric layers. The induced mechanical strain in the embedded or surface mounted piezoelectric layer can be used to reduce the high stresses in the plate. In this study a finite plate with a circular hole is used to demonstrate the effect of stress concentration reduction by using piezoceramic layers. Distributed piezoelectric patches are used on an aluminum plate with a hole as shown in Figure 1. An electric field is applied to the patches to cause expansion of the piezoceramic layers in the region around point B. This alters the flow of lines of force in the plate. This effect can be effectively used to reduce stress concentration in the plate.

Two types of embedding are discussed and are as shown in Figure 1. In the first type, the piezoceramic layer is embedded through the thickness. In the second case, the piezoceramic layers are surface mounted. In order to maintain a specific relationship between the applied electric field and the applied mechanical load, the value of the applied electric field E_0 was computed such that it would induce a stress equal in magnitude but opposite in sign to the mechanical applied load σ_{app} on an infinite piezoelectric plate under plane stress conditions.

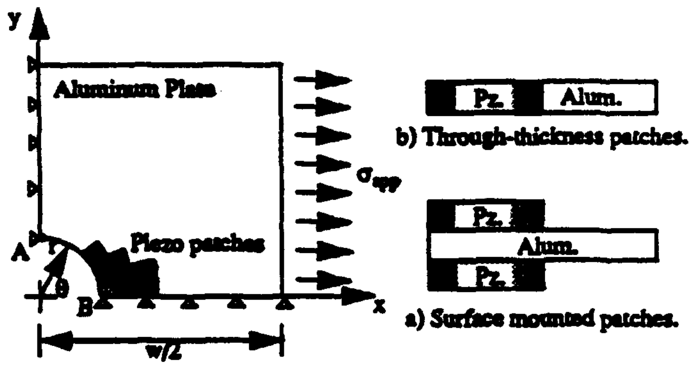

Figure 1. Aluminum plate with a hole and piezoceramic patches.

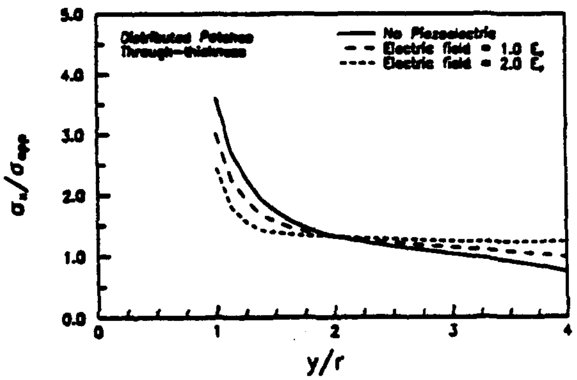

Figure 2. Distribution of stresses σ_x along the y-axis of the plate.

Stress distributions are obtained for the case of through-thickness embedding of piezoceramic layers. Figure 2 shows the distribution of stress σ_x along the y-axis for plate with and without the piezoceramic patches. The figure clearly shows the reduction in magnitude of the stress. For an Electric field $E_3 = 1.0\ E_0$ a 16% reduction in the stress σ_x was observed. Distribution of the tangential stresses σ_θ along the circumference of the hole is shown in Figure 3. The figure shows that tangential stresses reduce along the circumference. The other stress components in aluminum plate and piezoelectric layer did not exceed the maximum value of stress σ_θ at $\theta = 90^o$.

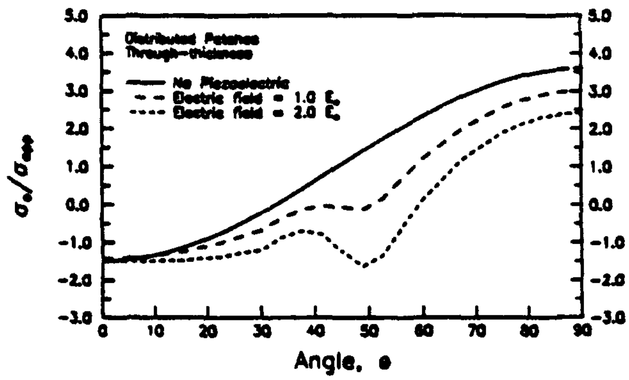

Figure 3. Distribution of stresses σ_θ along the circumference of the hole.

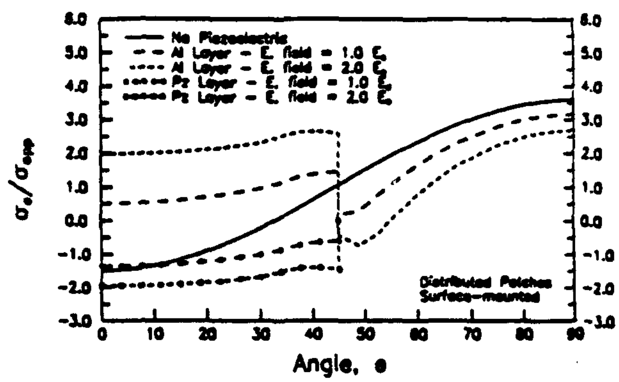

Figure 4. Distribution of stresses σ_θ along circumference of the hole.

Distributions are also obtained for the plate with *surface mounted piezoelectric patches*. It is observed that the reduction in the magnitude of stress σ_x (or σ_θ) at $\theta = 90^o$ is approximately 12% for $E_3 = 1.0\ E_0$ and that for $E_3 = 2.0\ E_0$ is about 24%. The reduction in stress concentration in the case of surface-mounted patches is found to be less than the case with through-thickness piezoelectric patches. Figure 4 shows the distribution of σ_θ along the circumference of the hole. From the figure, it can be seen that increase in the applied electric field would shift the area of maximum tangential stress in the plate to areas near the edge of the piezoelectric patches. Also from the figure, the magnitude of compressive stresses in the piezoceramics is lower than -2. everywhere. However, it was seen seen that at the applied electric field $E_3 = 2.0\ E_0$, the tangential stress in the aluminum plate at the hole circumference are high and almost equal to the stress σ_θ at $\theta = 90^o$. This suggests that for the embedded and or surface mounted case, the maximum applicable electric field is limited by the development of high stresses in other areas of the plate or piezoelectric layers, depending on the geometry and orientation.

From the stress distributions its is clear that application of negative electric field (in order to expand the piezoelectric layer) can alter the compressive zone in the plate near point B.(Figure 1). For the given geometry, the reduction in stress concentration is significant. However, the amount of reduction in the stress concentration is limited by the constraint that the stresses in other areas of the plate should not exceed the stress at point A (Figure 1), and a limiting value of the electric field can be derived in terms of the maximum compressive or the maximum tensile stresses developed in the plate Further study is necessary in order to find optimum shapes and sizes for the piezoelectric patches in order to obtain better reduction in the stress-concentration, and better mesh generation, using adaptive and shape optimization techniques can be used to achieve this.

ADAPTIVE AIRFOILS FOR HELICOPTERS

by

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INTRODUCTION

The ability to change the shape of an airfoil cross section in real time operation has been the dream of many engineers. Such a real time change of the shape of the airfoil cross section has the potential of providing numerous benefits in the field of helicopters. Some possible applications include vibration reduction, aeroelastic tailoring, flight control and minimization of performance losses due to nonuniform inflow and induced power.

The use of the concept of smart or adaptive materials, the real time computational capability, and the development of techniques of light weight implementation controllers have made the dream of real time change of airfoil shape a possibility. Currently, piezoelectric materials, shape memory alloys, and electro-rheological fluids are being used in these smart, adaptive or intelligent structures. In this paper, the use of shape memory alloys to change the camber of a rotor blade and develop collective control techniques.

SHAPE MEMORY ALLOYS

A shape memory alloy (SMA) has the unique capability to contract when subjected to heat. The shape memory property can be explained as follows. Let us consider a wire made of SMA. Let us also assume that this wire is stretched and deformed inelastically at a low temperature. If this wire is now heated to a temperature above a certain critical temperature the wire contracts and returns to its original geometrical shape. When cooled to a temperature below the critical temperature the wire assumes its inelastically stretched length or the shape. This type of shape memory effect was originally observed at the U.S. Naval Ordnance Laboratory in a Nickel- Titanium alloy. The alloy was named as NITNOL. The effect of memory recovery is known as the shape memory effect (SME).

The shape memory effect can be used to change the shape of the airfoil. Time responses, that one encounters when shape memory alloys are used for shape changes, are not as fast as the time

responses with piezoelectric transducers. However, with a shape memory alloy , we can hold the changed shape for a prescribed time duration. This makes the shape memory alloy an ideal smart or adaptive material for minimizing performance losses and collective control.

ADAPTIVE AIRFOILS IN COLLECTIVE CONTROL

In order to demonstrate the collective control of a helicopter by the use of active camber changes, we have modified a remotely piloted eight pound helicopter blades. This is a two-bladed helicopter. We have designed appropriate controllers to obtain desired camber changes and balance the blades. We have spin tested and flight tested the helicopter to demonstrate the structural effectiveness. Results of these and other flight tests with adaptive airfoil are discussed in the paper.

ABSTRACT

Shape Memory Alloy Actuators Embedded in Composite Beams

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Introduction

Helicopter rotors normally operate at a fixed rotational speed because of dynamic considerations. It is feasible to enhance the rotor performance by varying its speed at different flight conditions. However, there are problems associated with this concept. As rotational speed varies, the natural frequencies of the blades vary due to the change in centrifugal force. This can lead to resonances at higher harmonics, resulting in large dynamic stresses. Smart structures technology can be used to alleviate this problem by changing the frequencies of rotor blades by actuating the shape memory alloy (SMA) wires. In order to achieve this goal, an accurate analysis of composite beams, which form essential structural elements of composite rotor blades, with embedded SMA wires is needed.

Shape memory alloy wire, stretched under plastic deformation at a temperature has the capability to remember its original shape, when heated to its phase transformation temperature. Such a wire when embedded in a host structure induces a state of stress upon heat activation due to the constraints provided by the structure. Thus, prediction of the induced state of stress and the response of the host structure under its influence is of considerable interest. The author[1] experimentally illustrated that the natural frequencies of composite beams could be altered significantly by activating the embedded SMA. That study though confined to solid rectangular sections showed the efficacy of controlling the natural frequencies of composite beams by activating the SMA wires. However ,the analysis to predict the SMA wire-induced

1. Chandra, R. "Active Srain Energy Tuning of Composite BeamsUsing Shape Memory Alloy Actuators," SPIE's North American Conference on Smart Structures and Materials, Feb. 1-4, 1993, Albuquerque, New Mexico.

forces in a laminated composite medium and the response of composite beams under these induced forces is lacking.

The objective of the present study is to develop a micro-macro analysis to predict structural behavior of open-section composite beams with embedded SMA wires. Micromechanical analysis is developed to predict the axial force induced in composite medium due to SMA activation and macro-analysis is developed to predict the natural frequencies of rotating composite beam subjected to the SMA-induced axial force.

Analysis

The analysis consists of two parts. In the first part, micromechanical analysis is developed to estimate the state of stress in an elastic continuum due to SMA activation. Subsequently, beam formulation is developed to estimate the free vibration characteristics of open-section coupled composite beams under SMA- induced axial force.

Since the volume fraction of SMA wire in composite is low, the interaction effects between the SMA wire are negligible. Hence composite cylinders model (CCM) is adequate for micro-analysis. In this model, the stress and displacement fields in SMA wire and host structure are obtained using elasticity approach. Governing equations in displacements are solved under the assumption of generalized plane strain and the stresses in SMA and host structure are obtained. Subsequently, the macro- formulation for rotating open-section composite beam subjected to SMA-induced axial force is developed. The non-classical effects of this composite beam theory include section warping and transverse shear-related couplings. Various branches of open-section beams are modeled as general composite laminates and two-dimensional stress and displacement fields associated with these branches are reduced to one-dimensional generalized beam forces and displacements. The generalized beam displacements are connected to plate displacements through geometric considerations, whereas the generalized beam forces and their equilibrium

equations are obtained from energy considerations. The governing equations in flap, lag and torsional displacements are solved using Galerkin method and the natural frequencies of rotating composite beams with SMA wire- induced axial force are obtained.

EXPERIMENTS

In this paper, experimental study on solid beams with embedded SMA wires is carried out to validate micromechanical analysis. There are three important considerations for embedding SMA wires in composite beams. Firstly, the SMA wires must be surface-treated for good bond with the host structure. Secondly, the matrix of composite material should withstand the prestrain of the SMA wires. This requirement does not permit the use of normal composite material and calls for the use of materials with superior interlaminar shear strain at failure. IM7-8552 from Hercules satisfies such requirements and is selected for the present study. The third consideration is that the SMA wires must be constrained during the manufacturing, so that these do not return to their original position at curing temperatures which are higher than the phase transformation temperature of the SMA. In order to ensure uniformity of induced forces by these wires, the following procedure for embedding was used. The wires were electrically heated to remove the prestrain given during their manufacturing. The wires were chemically treated using an acidic bath recommended for stronger bond with titanium alloy. These were then given a known prestrain of 5%; this was achieved by applying 900 gms of dead weight to a 10 mil dia SMA wire. SMA wires were placed to create axial force in the beam and the response was sensed by strain gages. Since the SMA wires are embedded in composite beams and are subjected to curing temperature of the composite material, it was considered mandatory to check the influence of the curing cycle of composite on performance of the SMA wire. Hence, free SMA wires were constrained and heated to the curing temperature-time cycle and tested and this treatment was not found to influence the performance of free SMA wires. Heat activation was effected by electrical resistence heating, temperature was measured using thermocouple and the displacement of wire was measured using a linear scale.

RESULTS AND DISCUSSION

In this paper, the composite cylinders model is used to determine SMA induced axial force in composite solid beams. Analytical prediction of induced forces are validated by testing the solid beams. Fair correlation between analysis and experiment is achieved.

The beam analysis is now applied to compute the natural frequencies of rotating composite I-beams with embedded SMA wires. The value of the stress resultant due to SMA activation in a laminated composite medium depends upon the induced strain of free SMA wires, and properties of laminated medium and SMA wires. The induced strain of a free SMA actuator depends upon its initial strain and the operating temperature. In the analysis presented here, axial force is calculated using micro-analysis. The natural frequencies corresponding to lag-bending, flap-bending and torsional motions of rotating graphite-epoxy I-beam with SMA-induced forces are calculated.

FIRST ARO WORKSHOP ON SMART STRUCTURES AND MATERIALS
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ACTIVE FLEXIBLE THICK CYLINDERS WITH EMBEDDED SHAPE MEMORY ALLOY ACTUATORS

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Dr. Dimitris C. Lagoudas, Texas A&M University
Dr. Kevin Craig, RPI

ABSTRACT

The shape change of an initially stress-free, flexible, thick cylinder with an embedded, off-axis, shape-memory-alloy actuator is presented. When the actuator is heated and the martensite-to-austenite phase transition occurs, shape recovery of the actuator takes place, i.e., the actuator shrinks along its length. Upon shape recovery, the actuator exerts two distributed forces on the cylinder through the actuator/host interfacial shear stress that arises.

The first is a distributed off-axis compressive axial force which creates a bending moment. The second force arises due to bending of the cylinder: a normal force arises which opposes the direction of bending and is proportional to the curvature of the deformed cylinder. The cylinder continues to bend until a new equilibrium shape is established.

When the shape-memory-alloy actuator is cooled and the austenite-to-martensite phase transition occurs, the stiffness of the shape memory alloy decreases. The cylinder again moves until a new equilibrium shape is established. Stresses in the cylinder relax and the energy lost in the cylinder goes into stretching the martensitic shape-memory-alloy actuator.

A finite-element thermomechanical analysis was performed to model the shape of the cylinder that results upon actuator martensite-to-austenite phase transition (actuator heating). The stress relaxation effect of the reverse phase transition that occurs upon cooling the actuator was also

modeled.

Experimental active cylinder prototypes were designed and a micromechanics model developed by Lagoudas & Tadjbakhsh was employed to analytically predict the stress field around the actuator that arises due to actuator shape recovery. The micromechanics model was used in the design of the active cylinder prototypes to prevent actuator debonding and plastic deformation of the austenitic shape-memory-alloy actuator. The design analysis has shown that the most critical factor in designing with embedded shape memory alloy actuators is the host material's thermal bond characteristics. The thermal bond integrity of the actuator/host is dictated by the rod polymer's thermal resistance, the stiffness of the rod polymer, and the prestrain imparted to the shape-memory-alloy actuator.

Active cylinder prototypes were fabricated, activated, and the resulting deflections were measured for several heating and cooling cycles. Use of the micromechanics model to predict the actuator/host interfacial shear stress associated with recovery worked well. The micromechanics model predicted that the interfacial shear in the cylinder would not exceed the critical debond stress, and the actuator remained bonded in the experiments. The micromechanics model also helped in finite element mesh refinement. The finite element model was accurate for the heated shape and suggests that this is a good method of modeling the mechanics of recovery of embedded shape-memory-alloy actuators. The finite element model was less accurate for the stress relaxation problem.

Electrodeposition Processing of Shape Memory Alloys

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The field of smart structures continues to grow at a rapid rate. The very complex nature of this technology is evidenced by the need to integrate a number of operating disciplines from both the scientific and engineering community. The materials used in these structures, particularly in the sensing and activating stages, are critical components to the ultimate success of the system. One category of metals that has been extensively investigated for use is shape memory alloys. Nitinol has been the most popular to date, but other alloys may offer some attractive features that would make them likely candidates as well.

It is common for many materials to exhibit structure sensitive properties. In turn, the structure of many metals and materials is often a function of the processing techniques used in their manufacture. The majority of the shape memory alloys in current use are made by more conventional melt/cast/shape techniques. Recently a unique process was developed at UMR in which certain shape memory alloys were deposited electrolytically from aqueous solutions. The ability to synthesize the shape memory alloys using electrochemistry offers a number of potentially attractive opportunities. The films can be deposited in-situ in very thin layers or at a controlled thickness of any desired level. Also, bulk production can be accomplished in a reasonably economic manner.

Electrodeposition of shape memory alloys can be simply described as a electrochemical reduction of metallic ions onto the cathodic surface. The growth process also involves a stacking of atomic lattices through a highly electrically charged layer. As a result, the atomic lattice can be distorted developing internal stress due to occlusion of foreign substances. The non-equilibrium nature of the electrodeposition process can cause unusual properties of the alloy films which differ from those of alloys of the same composition but at equilibrium.

For shape memory alloys, certain properties, such as transformation temperature, are largely dependent on chemical composition. Electrodeposition can offer an additional advantage.

The composition of alloys can be altered by simply changing process parameters such as current density, temperature or current wave form. A number of alloy systems including Cu-Zn, Au-Cd and Indium alloys have been electrodeposited using several different electrolytic techniques such as cementation, DC plating, pulse plating and pulse reverse plating. Each technique has its own merits and characteristics and will be described. The alloy deposits in turn have properties that vary with the processing technique used..

The results show that the transformation behavior, particularly transformation temperature and temperature interval of electrodeposited alloy films are quite different from thermal alloys. Both of these properties are important characteristics of the shape memory alloys. Different tests including X-ray diffraction, differential scanning calorimetry, electrical resistance and simple bending tests etc. were conducted to characterize the alloy films prepared electrochemically.

Additional research is needed to investigate in greater detail the process factors affecting the shape memory properties of the alloy films. One disadvantage of the electrodeposition is that some major elements commonly used for shape memory alloys, such as aluminum and titanium, are impossible to deposit from aqueous solutions. The electrodeposition process can be conducted at nearly ambient temperature and is not capital intensive. Therefore, whenever thin film types of shape memory alloys are necessary, electrodeposition appears to offer some attractive alternatives as a choice for manufacturing such materials.

A Micro-thermodynamics Analysis of Shape Memory Alloy Composites

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and
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Thermomechanical constitutive equations for shape memory alloy (SMA) composite materials consisting of a SMA fiber embedded in an elastomeric composite are developed using a two-part method. First, phenomenological constitutive equations are determined for the monolithic SMA material. Second, the SMA composite constitutive equations are derived using a micromechanics method which consists of averaging the solution to a boundary value problem formulated over a representative volume element of the composite material. In each case, the constitutive equations consist of the free energy, which defines the thermodynamic state, and a dissipation potential, which gives the evolution of the phase transformation and the transformation strain.

For the monolithic SMA material, the shape memory effect (SME) due to both the phase transformation and the reorientation of martensite are modelled as chemical reactions involving three species - austenite, self-accommodating martensite, and detwinned martensite. The free energy, a function of stress, temperature and the volume fraction of the two independent species, consists of the elastic and chemical contributions from the three species, plus the free energy of mixing, which is due mostly to misfit stresses between the species. It is assumed that the three reactions among the species are uncoupled, and that each rate of reaction is given by a rate independent dissipation potential. For the case of proportional loading, the rates of reaction can be integrated in closed form to obtain an equation of state between the species mass fractions and stress and temperature.

The composite free energy, which is derived by homogenizing the solution to the local boundary value problem, consists of the free energies of the SMA fiber, the elastomeric matrix, and the free energy of mixing. The mixing energy consists of two parts: (1) The misfit strain energy due to the incompatibility of the thermal and inelastic eigenstrains; and (2) The interaction energy between the fibers and the applied stress. The misfit energy contains terms that are quadratic in temperature and quadratic in inelastic strain, and a coupling term that contains the product of temperature and inelastic strain. The quadratic temperature term contributes to the composite specific heat. The quadratic inelastic strain term accounts for the inelastic hardening of the composite relative to the monolithic SMA fiber. The term coupling temperature and inelastic strain causes a spatially homogeneous temperature change of a stress-free composite to produce a transformation strain. The composite therefore exhibits the two way shape memory effect (TWSME) even though the

SMA fiber can only undergo the *one way shape memory effect*. The composite inelastic strain rate, the hardening rate, and the TWSME are obtained from the composite dissipation potential, which is derived by homogenizing the solution to the local boundary value problem.

The composite micromechanics problem is solved using both the finite element method and the Mori-Tanaka method, a simple mean field theory. It is found that since the fibers, but not the matrix, undergo the inelastic deformation, the Mori-Tanaka method accurately models the thermomechanical response of the composite relative to the finite element method.

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RESPONSE OF AN ELASTIC ROD WITH MULTIPLE EMBEDDED SMA ACTUATORS

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Abstract

In the field of active shape control using shape memory alloy actuators, there are two methods of embedding shape memory alloy actuators in a host medium. One is through the use of embedded, sliding fibers which involve the creation of sleeves within the host medium. In this case, the force of actuator is a concentrated force applied to the rod at the end of the sleeve and the system can be modelled as a Beck's rod with an eccentric follower force[1,2]. the other method is through the use of embedded, continously bonded SMA actuators. These transmit distributed forces through the interfacial shear stresses that develop in the actuator/host bond when the SMA recovery takes place.

The present paper sets out to investigate the case of embedded, bondded SMA actuators. To that end the force of actuator is assumed to be a distributed shear force applied to the rod along the length of the fiber. Load-deflection curves for various offset disturbances and the shape of deflected rod at various load levels are obtained by solving the nonlinear equations of equilibrium of an elastic rod with eccentric distributed follower forces. It is shown that various configurations for active shape control of flexible rods can be obtained using nonlinear theory of elastic stability of nonconservative systems.

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A Ginzburg-Landau Model for One-Dimensional Deformations of Phase Transforming Materials

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Many polymeric and shape memory materials exhibit strain-hardening, strain-softening followed by strain-hardening type response when subjected to mechanical loads [1]. For one-dimensional problems, the strain-hardening (strain-softening) regime is the one in which the axial tensile stress increases (decreases) with an increase in the axial tensile strain. Thus, the axial stress T vs. axial strain λ curve is non-monotone and is usually taken to include a single loop. Under a suitable external tensile traction T_o, the axial strain at a point within the body assumes either one of the two values that correspond to points on the hardening portion of the stress-strain curve for the applied traction T_o. Thus, the axial strain suffers a jump at a finite number of points within the body. Such phenomenon has been referred to as "necking" by some investigators, *e.g.*, see [2].

Coleman [3] stated that the cold drawing of a polymer fiber transforms the material from a state of low or moderate molecular orientation to a state of high molecular orientation which resembles a first-order phase transition. Here we postulate that this phase transition changes the microstate of the material which is responsible for its subsequent rehardening. We employ the Ginzburg-Landau approach [4] and incorporate a phenomenological parameter ξ to describe fully the state of the material.

We assume that the free energy density f has the form

$$f(\lambda, \xi, \xi_x) = f_o(\lambda) + f_2(\lambda)\xi^2 + f_3(\lambda)\xi^3 + f_4(\lambda)\xi^4 + f_5(\lambda)\xi_x^2, \tag{1}$$

where $f_i(\lambda)$, i = 2,3,4,5 are material-dependent functions of λ and $f_o(\lambda)$ is the classical free energy density that exhibits the softening behavior without any subsequent rehardening. Let the highest-order term involving λ in the expression for the free energy density be λ^{2n} where n is a positive integer. Since ξ is responsible for rehardening, which is dominated by the highest-order term λ^{2n}, therefore, it is reasonable to assume that

$$\lim_{\lambda \to \infty} |f_o(\lambda)/\lambda^{2n}| = 0, \text{ and } f_i(\lambda) = \hat{f}_i \lambda^{2n}, \quad i = 2,3,4,5 \tag{2}$$

where $\hat{f}_i$ for i = 2,3,4, and 5 are constants that satisfy

$$\hat{f}_2 > 0, \ \hat{f}_3 < 0, \ \hat{f}_4 > 0, \ \hat{f}_5 > 0, \ \hat{f}_3^2 \leq 4\,\hat{f}_2\,\hat{f}_4, \ 9\hat{f}_3^2 > 32\,\hat{f}_2\,\hat{f}_4. \tag{3}$$

For a bar occupying the domain $\Omega = [-L, L]$, we determine the equilibrium fields by minimizing the functional $F(\lambda(x), \xi(x))$ defined as

$$F = \int_\Omega f(\lambda, \xi, \xi_x)dx - [T_o\, u]_{-L}^{L} \tag{4}$$

where T_o is the external axial tensile traction applied at the ends of the bar, u is the axial displacement of a point, $\lambda = u_x$, is the axial strain and $u_x = \partial u/\partial x$. The corresponding Euler-Lagrange equations are

$$T_x = 0, \quad T = f_o' + 2ng\lambda^{(2n-1)}, \tag{5}$$

$$-2\hat{f}_5\,[\lambda\xi_{xx} + 2n\lambda_x\xi_x]\lambda^{(2n-1)} + \lambda^{2n}\,(2\hat{f}_2\xi + 3\hat{f}_3\xi^2 + 4\hat{f}_4\xi^3) = 0, \tag{6}$$

and the associated natural boundary conditions are

$$T = T_o, \ \text{ and } \xi_x = 0, \ \text{ at } \ x = \pm L, \tag{7}$$

and a prime indicates the derivative of a function with respect to its argument.

For $\hat{f}_5 = 0$, i.e., when f is independent of ξ_x, it is shown that there are two possible jump solutions $(\lambda_o, 0) \rightarrow (\lambda_3, \xi_3)$ and $(\lambda_1, \xi_3) \rightarrow (\lambda_3, \xi_3)$. On the assumption that $\hat{f}_5$ is relatively small and plays the role of a regularization parameter, it is shown that the order-parameter $\xi(x)$ must be nondecreasing for the first jump solution, and symmetric about the jump point of $\lambda(x)$ for the second solution.

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A Smart Structures Approach to Noise and Vibration Control

Keynote Speech by

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Smart Composites: Damage Detection and Shape Control

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Abstract

Composite materials offer a wide range of mechanical and physical properties due to their structural design being based on at least two basic constituents. Properties of the constituents often differ from each other which is sometimes a disadvantage. But it can also be taken as an advantage allowing a composite to carry the structural load, but also to have additional scopes. Fibre reinforced polymers are by nature a candidate material for smart structures.

Unisotropy in mechanical properties and thermal expansion coefficients allow to design a composite material having curved shapes, i.e., thin unsymmetric laminates do not conform to the predictions of classical lamination theory. Rather than being saddle shaped thin unsymmetric laminates are cylindrically shaped or even exhibit a snap-through phenomenon, which means they have two room temperature shapes. This phenomenon can be used as an advantage to amplify the shape memory effect of shape memory alloys.

Carbon fibres, used as a reinforcement constituent, are can bear high loads, but they also are electrically conductive. Therefore in carbon fibre reinforced composite laminates, this effect can be used to directly monitor the actual load dependent strain, but also the damage development in a composite laminate.

In the presentation an overview will be given on smart composites, their design and possible applications.

Development of an Interfaced Embedding Technique for Smart Composite Structures

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Extended Abstract

Smart composite structures with integrated actuators and sensors have pobential applications in providing active shape and vibration control and damage detection capabilities to aerospace systems such as rotorcraft and large space structures, The actuators and sensors can either be surface-bonded or embedded to the host. Laminated composites are ideal for use with embedded devices due to the structural tailorability of the material.

Piezoceramics exhibit mechanical deformation under an applied voltage and are finding widespread uses as induced strain actuators in smart structures. The standard manufacturing technique for embedding piezoceramics inside a laminated composite is the cut-out method. This technique involves cutting rectangular holes slightly larger than the embedded device into the corresponding plies during the lay-up procedure. The actuator is then placed into the resulting cavity and additional plies are stacked over the inclusion. The discontinuous plies lie in the plane of the actuator while the continuous plies lie above and below.

Research has been conducted concerning both analytical and experimental aspects of integrating piezoceramics within a composite laminate by the cut-out method. Crawley and de Luis[1] performed an investigation of both surface-bonded and embedded piezoceramic actuators as elements of intelligent structures. They utilized the standard cut-out technique with both graphite/epoxy and glass/epoxy laminates. Static tensile tests of glass/epoxy coupons indicated that the discontinuity created by the inclusion reduced the ultimate strength of the laminate by 20%.

Warkentin and Crawley[2] developed a technique for embedding integrated circuits on silicon chips within graphite/epoxy specimens, again utilizing the cut-out method. Static testing of the specimens. showed a 15% decrease in maximum stress. Also, both static and dynamic tests of the specimens showed lead breakage as a failure mode.

Joshi and Chan[3] investigated a new manufacturing technique for fabricating laminates with embedded piezoceramics. They utilized the normal cut-out technique

and placed glass layers above and below the piezoceramic to provide insulation from the conductive graphite/epoxy plies. Shah, et.al.[4] performed the corresponding free-edge interlaminar stress analysis to determine the optimal placement location of piezoelectric layers in the laminate. The addition of the em/epoxy layer actually reduced the interlaminar stresses. Also, it was observed that varying the placement of the piezoelectric layer did not alter the maximum interlaminar normal stress.

Finally, Chow and Graves[5], analyzed the three-dimensional stress and displacement fields around an inert rectangular implant placed inside a laminated composite using the cut-out technique. They concluded that the applied load on the laminate, N_{11}, was redistributed around the inclusion in the 1-2 and 1-3 planes. Also, the resulting interlaminar stresses were an order of magnitude lower than the applied far-field stress.

The cut-out method has a significant effect on the integrity of the host structure. The laminate suffers a net area loss of material due to the discontinuous plies, and the load must be transferred from ply to ply around the inclusion. Interlaminar stresses arise in the interface adjacent to the actuator and may lead to delamination of the host composite structure. This may precipitate failure of either the host, the host-piezoceramic interface, or the piezoceramic itself. Therefore, an alternative embedding technique must be investigated.

The interlacing method of embedding piezoceramics within a composite structure, developed at the University of Maryland, involves varying the location of the discontinuous and continuous; plies through the thickness of the laminate. Thus, the plies may no longer be planar as they interlace above or below the actuator. The cut-out method is actually an interlaced configuration where all of the discontinuous plies are located in the plane of the inclusion.

Although an interlaced laminate suffers the same net area loss of material as a cut-out laminate, all of the discontinuous plies are no longer located in the plane of the inclusion. Thecontinuous plies laced over the piezoceramic are capable of transferring load around the actuator in the inclusion plane. Triangular resin pockets resulting from interlacing provide a gradual transition between the piezoceramic and the composite, whereas rectangular resin pockets in the cut-out laminate result in a sharp interface.

A quasi-three-dimensional finite element model was developed to analyze the interlaminar stress at and near a static glass inclusion embedded within a unidirectional graphite/epoxy laminate for various interlaced configurations. This analysis utilized eight-node assumed stress hybrid hexahedral elements along with six-node assumed displacement pentahedral elements. Each ply of the laminate was modeled as a single element in the y and z-directions and a row of elements in the x-direction. A refined mesh was used in the area of the resin pockets. Only one-quarter of the laminate was modeled due to symmetry.

In the finite element models, a four-ply thick glass inclusion was located at the center of the laminates. The models included eight continuous plies, four discontinuous plies, and two thin resin-rich interply layers. The stress concentrations in the various interlaced models under an applied tensile load were compared to the results corresponding to the cut-out method, which was used as the control case in this study. The interlaminar normal and shear stresses, σ_{zz} and σ_{zx}, located in the thin resin-rich interply layers adjacent to the inclusion were determined from the analysis.

Composite specimens were fabricated to examine the effects of the interlacing technique for static inclusions. The specimens were constructed using A54/3501-6 preimpregnated graphite/epoxy plies. Five different interlaced configurations and a cut-out configuration were laid up with static inclusions. The static inclusions for this study were 1.0 mm thick glass microscope slides measuring 25.4 mm wide by 76.2 mm long. The lower continuous and discontinuous graphite-epoxy plies were laid up on an aluminum tool to produce resin pockets with a 1:10 height/length ratio, resulting in an internal pocket angle of 5.71°. Four glass slides were laid end to end spanning the width of the laminate and then covered with the remaining top plies. Each of the laminates had a total thickness of twenty-four plies.

The. laminates were cured per the manufacturer's recommended cycle.Specimens were then machined from the laminate and adhesively bonded with glass/epoxy tabs. Each specimen was instrumented with three longitudinally mounted strain gages, one located far-field and the remaining two located at the edges of the inclusion. Additionally,one specimen of each different configuration had a transverse gage mounted far-field.

Prior to testing x-rays of the specimens were taken in order to determine the extent of damage to the glass inclusion due to the embedding and machining procedures. Dye penetrant was applied to the edges of the specimens to aid in the ation of the damage. Cracks in the glass slides and local delamination in the specimens near the inclusion edges were noted. The specimens were then tested in tension under stroke control until ultimate failure. Delamination was detected by the occurrence of a drop in load. X-rays of the specimens were again taken after the completed test. The load, strain, and displacement data from the test was acquired by a computer at regular intervals and plotted.

The analytical model and experimental data were correlated. Interlacing was effective in reducing the interlaminar stress state at and near the inclusion. Thus,the onget of delamination was delayed. Specifically, the experimental program showed that the interlacing technique affected both the load at which delamination was detected and the ultimate strength of the specimens.

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A Composite Beam Finite element Model With Distributed Piezoelectric Crystals

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Abstract

Most computational/analytical studies on piezoelectric strain actuation of laminated composite beams have been limited to thin solid sections with crystals aligned with the beam axes. In the present study, effect of distributed piezoelectric crystals is included in a finite element model for thin-walled composite beams with complex cross-sections undergoing out-of-plane warping. Warping nodes with one degree of freedom are used to represent warping displacements normal to the cross-section.

For the case of a beam with several crystals, or for the case of crystals not aligned with the beam axes, it is desirable to model crystals within an element. When the crystal is contained within an element, the element needs to be partitioned into sub-domains, and integration carried out separately over each sub-domain. Also, special care is taken to alleviate transverse shear locking. An innovative method is presented to model crystals that are not aligned with the beam axes. While it would be straightforward to model such skewed crystals using a plate model, capturing its behavior in a beam model is a challenge. The warping nodes make the formulation 'pseudo two-dimensional', and allow it to capture the twist induced by placing the crystals off-center or in a skewed configuration. A consistent formulation which carefully considers such aspects associated with piezoelectric stain actuation, is developed. The formulation can be used to model straight and curve laminated composite beams with complicated cross-sections, pretwist, taper. The effectiveness of the present approach is validated by comparing with shell-element solutions and existing experimental data.

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ELASTIC ANALYSIS OF LAMINATED COMPOSITE PLATES IN CYLINDRICAL BENDING DUE TO PIEZOELECTRIC ACTUATORS*

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Extended Abstract

An analysis of laminated composite plates forced into cylindrical bending by the application of voltages to piezoelectric actuators attached to the top and bottom surfaces of the composite plate is performed. Each laminate is modeled as a three–dimensional elastic continuum and the piezoelectric actuator is modeled as a two–dimensional surface film. Mixed conditions at the edges are employed to simulate simple supports. The differential equations of linear elasticity are satisfied for each laminate along with the interface conditions between laminates. The shear traction conditions at the surfaces of the composite plate result in a differential relation as a result of representing the actuator as a thin film. The entire configuration deforms as in uniform cylindrical flexure for symmetric composite plates, even though no bending moment is applied, as a result of the piezoelectric constitutive response of the actuators to applied voltages. The solutions are obtained using Fourier series.

The two–dimensional equations for the laminated composite plate are obtained using the variational procedure of Mindlin. However, the reduced plane–stress constants for each laminate are employed as in the conventional treatments of composites. This is required for consistency with the assumption on the thickness dependence of the displacement field. The piezoelectric thin film actuators are incorporated in the two–dimensional description of the entire

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composite plate by means of the above mentioned differential relation for the actuator. Since the voltages are constant across each actuator, the plate equations are satisfied identically and the solution is determined by the edge conditions.

The results obtained from the linear elastic solution are compared with those obtained using the two–dimensional equations of the coupled extension and flexure of thin composite plates, which are the ones usually employed in practice. When the properties of adjacent laminates are very different the comparison reveals that for large span length–to–thickness ratios the agreement is quite good but for small ones it is not good at all. In addition, the nature of the stress concentration arising under the edge of the actuator is exhibited.

First ARO Workshop on Adaptive Structures

Constitutive Modeling of a Programmable Structure

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Abstract

Interest has developed in the use of embedded piezoelectric actuators and sensors in composite structures, such as helicopter rotors, due to their ability to provide not only active stiffening and dissipation, but also information regarding the durability of the structure. Due to relatively high interlaminar stresses inherent in the use of embedded piezoelectric actuators, low cycle life is to be expected in real world applications using existing technology. It is necessary, therefore, that new technology and designs be developed to extend the life of embedded actuators and sensors. The purpose of this research is to develop basic, yet accurate performance models that will provide some insight into the location and magnitude of the stress field of embedded piezoelectric elements. Such models will allow an intelligent approach towards resolving the problems of interlaminar failure.

Analytical and finite element modeling of a programmable composite structure have been investigated and compared with experimental results to better predict the performance of embedded piezoelectric actuators and sensors. The first objective of the research was to develop and compare a 2-D finite element model and a basic constitutive model of piezoelectric patches embedded in the structure. The second objective was to analyze, using a 3-D finite element model, the stress field of such an embedded actuator with the 3-D effects taken into account. The third objective was to predict the performance of the embedded patch with the 3-D model and verify the predictions experimentally using high-resolution measurement devices on an actual structure with embedded piezoelectric elements. The final objective was to investigate the changes in both high stress areas and effective force when the piezoelectric patch shape is altered.

The programmable composite structure to be modeled and tested is a cantilever beam with two Lead/Zirconate/Titanate piezoelectric patches embedded near top and bottom surfaces.

The beam consisted of eight layers of 3M 1003 fiberglass. The piezoelectric patches are incorporated into the second and seventh layers of the beam. Depending upon the control system used, either one patch could be used as an actuator and the other as a sensor, or both patches could serve each purpose due to the self-sensing capability of piezoelectrics.

The primary focus of this research is to develop two-dimensional finite element and constitutive models of embedded patches in the programmable structure, assuming plane strain conditions. These models are the basis for understanding the stresses within the patch and the loads which they translate to the structure. ANSYS 5.0 was selected to define and solve the finite element model, principally because of its 2-D and 3-D Coupled-Field Elements, which can be defined so as to simulate piezoelectric materials. The three-dimensional finite element model is based upon the same structure as the two-dimensional model, except that instead of assuming plane strain, the effects of structures with finite depths are taken into consideration. The purpose in creating this model is to better analyze the interlaminar shear stresses and the stress concentrations by more accurately modeling the physical structure. The only consolation made in the name of expediency is in assuming elastic effects in the composite are independent of direction.

With the three-dimensional model created, the next step is to predict the performance of the beam under static conditions by modeling those conditions in ANSYS. For a given DC voltage, the displacement of several points along the beam is measured and compared to the finite element model output for the same initial and boundary conditions. In order to accurately measure the performance of the beam, the structure is mounted to an optical bench to isolate it from room vibrations. The measuring device is a Kaman single ended sensor that can measure up to 2.3 mm and has a resolution of 0.3 microns. This sensor is mounted to a high precision base and rail to assure consistent placement at measuring points along the beam.

Another point of interest in the field of embedded piezoelectric patches concerns determining the effects which patch shape has on performance. It is very reasonable to assume that by optimizing its shape, piezoelectric patches could be designed to reduce the delamination stresses without sacrificing sensitivity or force output. Shape revisions will be performed on the patches in the 3-D finite element model and the corresponding performance changes analyzed for improved performance characteristics.

Stress Induced Phase Transformations in Piezoelectric Laminates with Shape Memory Alloy Layers

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Abstract

Piezoelectric materials under the application of electrical cyclic loading show a reversible behavior (Moulson and Herbert, 1990). SMA's on the other hand exhibit large hysteresis in a thermomechanical cycle (Jackson, et al., 1972). A hybrid piezoelectric-SMA system is expected to dissipate work during an electrical cycle due to the electromechanical coupling. To study this effect a triplet consisting of a central SMA strip with piezoelectric layers on both sides is considered in the present work. The electroelastic problem of a laminate with piezoelectric layers is solved by extending the solution for the elastic problem (Pagano, 1969). The elasticity solution is extended to the coupled electroelastic field by adding to the Airy stress function the electric potential.

A similar procedure is applied incrementally to the case of a hybrid composite plate with piezoelectric layers attached to shape memory alloy (SMA) thin strips. The non-linear effect of piezoelectrically induced transformation strains is modelled as a sequence of linear piezoelectric problems with piecewise linear SMA constitutive response. The incremental formulation of the problem incorporates both stiffness changes and transformation strains in the SMA induced by the piezoelectric layers. As an example, the response under a full loading-unloading electrical cycle of a NiTi SMA layer attached to PZT piezoelectric layers is evaluated. A full loading-unloading cycle in the applied electric field is shown to lead to energy dissipation in the laminated plate due to the dissipative process of stress induced martensitic phase formation (Fig. 1 and 2).

Acknowledgement
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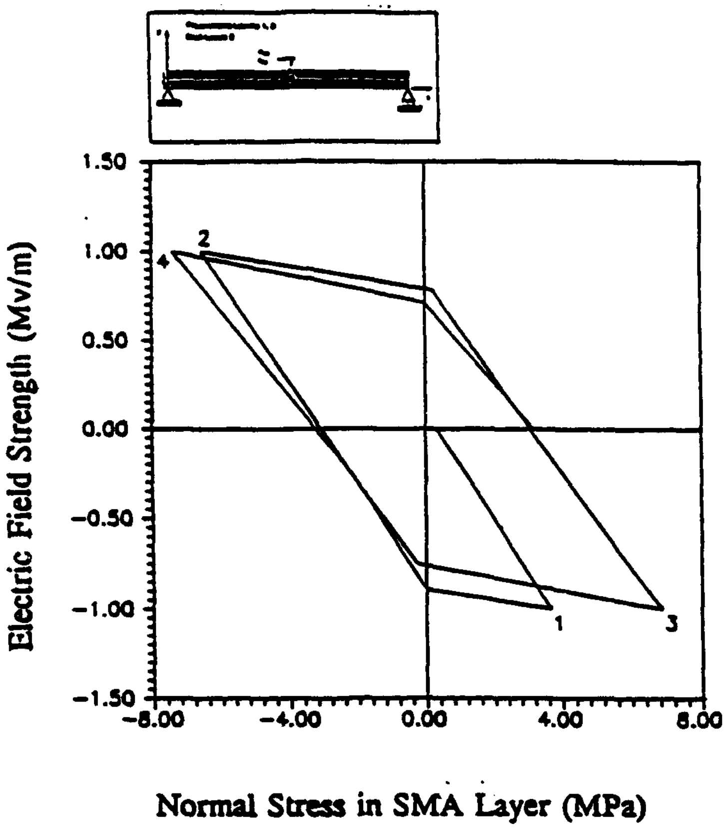

Fig. 1. Normal stress in the middle of the SMA layer induced by two full cycles of the applied electric field.

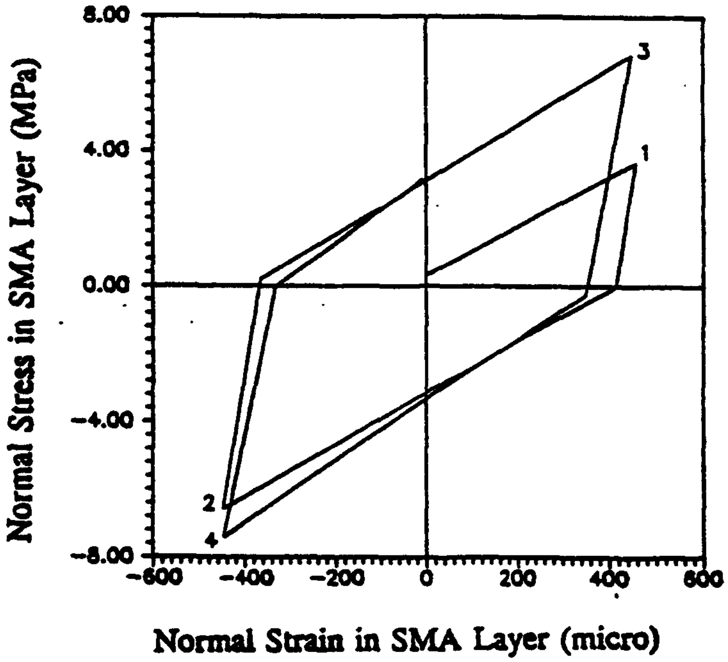

Fig. 2. The stress-strain response of the SMA layer induced by the applied electric field.

Bending and Torsion Models of Beam with Induced Strain Actuators

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Introduction

Helicopters suffer from excessive vibration, high fatigue loads, poor handling qualities and intolerable noise. The objective is to improve the dynamic performance of the helicopter and reduce vibration to an acceptable level. Research on Higher Harmonic Control (HHC) and Individual Blade Control (IBC) of helicopter vibration has shown that these concepts can be used to reduce vibration transmitted to the pilot's seat. However, HHC and IBC have high weight penalties and they are limited in their application to reduce stresses, improve performance of the helicopter, and reduce noise. It is envisioned that incorporating smart structure technology in rotor blades can give desirable shape control characteristics to improve the helicopter in all of these areas at a reasonable weight penalty. The need for modeling of intelligent structures, in particular beams undergoing extension, bending and torsion deflections, is important in the application of smart structure technology to rotor systems. For the comprehensive aeroelastic analysis of a rotor system, it becomes necessary to use 1-D beam models undergoing bending and torsion deformation. This paper presents a 1-D model to include torsion. Since the actuation mechanism is inherently a 2-D phenomenon, use of a 1-D formulation will have some limitations that will be evaluated experimentally.

Analysis

In this paper, a one-dimensional (1-D) model of coupled extension, bending and torsion of a beam due to induced strain actuation is developed by invoking the Principle of Virtual Work. Non-classical warping effects are introduced in the displacement field to capture torsional couplings. For simplicity, this particular analysis is limited to a thin rectangular beam of uniform cross-section with a single actuator bonded to one surface, shown in figure 1, however the formulation can be easily adapted to other geometries. The displacement field of a beam undergoing axial deflection and Bernoulli-Euler bending is modified to incorporate a torsion response by including a warping function as suggested by Gjelsvik[1], who considers that the warping function, ω, is composed of contour warping, $\bar{\omega}$, and thickness warping, $\bar{\bar{\omega}}$. For thin rectangular beams, the contour warping is negligible and the associated warping function is $\omega(y,z) = \bar{\bar{\omega}} = yz$ and is depicted in figure 2.

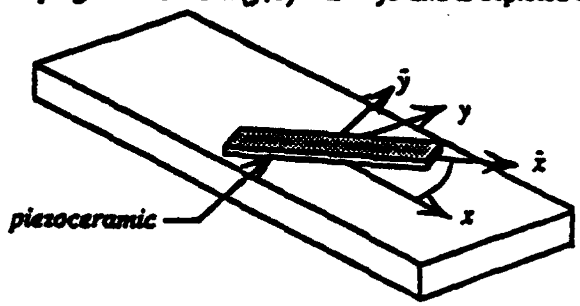

Figure 1 Rectangular beam configuration

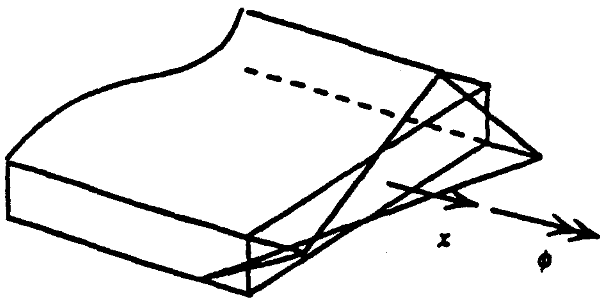

Figure 2 Warping function for a thin rectangular beam

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* Smart Structure Fellow
** Professor and Director

Delamination suppression and detection in a composite laminate using piezoceramic layers

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ABSTRACT

This paper shows an approach to using piezoelectric layers to detect and suppress delamination in laminated composites. A quasi-3D modelling technique which only models the structure in the two dimensions but allowing a degree of freedom in the 3rd direction, has been developed to analyze the interlaminar stresses of laminates under a uniform bending, uniform twisting and uniform extensional loads and piezoelectric loads. In this study a $(+45^{o}/-45^{o}/0^{o}/90^{o})_s$ quasi-isotropic laminate stacking sequence is used as the baseline laminate for the analysis. Figure 1. shows a typical configuration of the laminate with a piezoelectric layer.

Previous studies on appropriate delamination failure criteria by a number of authors have shown that delamination under axial extension usually nucleates from the tip of a transverse matrix crack in the 90^{o} ply and then spreads along the length of the $0^{o}/90^{o}$ interface in both directions. Strain energy release rates for the different combinations of the stacking sequence for a crack length of $a/h = 10$ were also computed. From these strain energy values and appropriate selection criteria a delamination was assumed to exist in the 0/90 interface of each laminate stacking sequence.

In order to see the effect of the applied electric field and the uniform applied strain on the delamination characteristics of the laminate, interlaminar stresses and strain energy release rates are obtained for the different cases. When the piezoelectric layer is used as an actuator, application of the electric field causes mechanical deformation of the host structure and the piezoelectric layer itself. A negative electric field reduces the tensile normal stresses and the interfacial shear stress at the delamination front for this configuration. Figure 2. and Figure 3. show that application of negative electric field on the piezoelectric layer reduces the strain energy release rates as the delamination length approaches a horizontal distance of within 20h from the edge of the piezoelectric layer. The reduction in the strain energy release rates in this configuration, suggests an improvement in the delamination resistance of the laminate with a negative electric field.

Figure 4. shows the electrical response of the edge of the piezoelectric sensor to delamination growth. Along the x-axis is plotted the delamination length and the y-axis shows the electric field E_3 developed per unit applied uniform strain ε_o. The legend shows the placement of the piezoelectric layer. The electric field at the tip of the piezoelectric layer is shown here since it is the closest to the crack tip. The presence of delamination causes the local stress field to change thereby altering the electric field in the piezoelectric. The electrical response shows a change when the delamination is within about 20h from the edge of the piezoelectric layer.

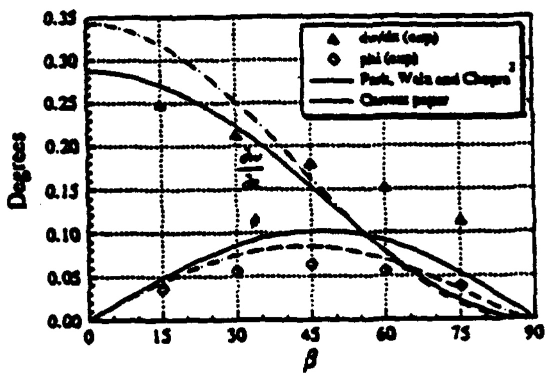
The assumed displacement field is given in equations (1), (2) and (3). The subscript 'x' is used to denote partial differentiation with respect to the x-axis.

$$u(x,y,z) = \underbrace{u_o(x)}_{extension} - \underbrace{zw_{,x}(x)}_{bending} - \underbrace{\phi_{,x}(x)\omega(y,z)}_{warping} \tag{1}$$

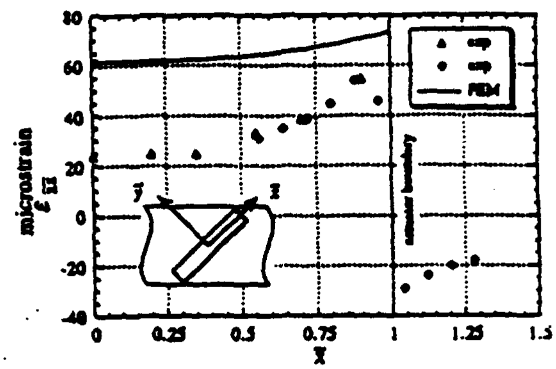
$$v(x,y,z) = -z\phi(x) \tag{2}$$

$$w(x,y,z) = w_o(x) + y\phi(x) \tag{3}$$

Substitution of the warping function into the virtual work expression, integration over the cross-section, and integration by parts in the beam axis provides the governing differential equations and natural boundary conditions. Solving these equations numerically provides the strain, tip twist angle and tip bending slope results which are compared against experimental data and predictions previously obtained by Park, Walz and Chopra[2] in figure 3.



Theoretical tip rotations



$\varepsilon_{\xi\xi}$ strain distribution for $\beta = 45^o$

Figure 3 Reslults comparison

Conclusions

A 1-D model to predict the coupled extension, bending and torsion response of a beam subject to induced strain actuation has been developed. Initial correlation with experimental data demonstrates that the model has the capacity to predict the response within 1-D limitations. The highest error in the torsion prediction is 32% at $\beta = 45^o$ and approximately 20% in bending slope at $\beta = 0^o$, considering only $\beta \leq 45^o$. Incorporation of shear lag effects and improvement of the integration boundaries are expected to narrow these discrepancies. Strain predictions, however, are not expected to correlate as well with test data, especially in the vicinity of the actuator. To obtain an accurate strain distribution, a 2-D analytical platform is required. Further parametric experimentation will more fully illustrate the limitations and strengths of the presented 1-D formulation.

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The electrical response obtained is fairly sensitive to the presence of delamination in the laminate. It is seen that the presence of delamination in an interface of the laminate can be detected by a piezoelectric layer in its vicinity. Delamination growth in the laminated composite can be detected by changes in the electric field induced due to the local stress changes. Application of electric field to a piezoelectric layer and the mechanical strain induced can be effectively used in delamination suppression. A detailed study of strain energy release rates and interlaminar stresses will be presented in the paper. This technique can potentially be a useful tool in damage control in smart structures.

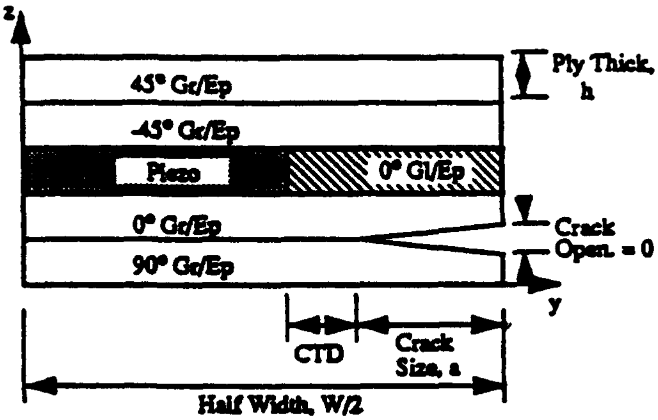

Figure 1. Laminate configuration and FEM mesh for a quarter of the cross-section.

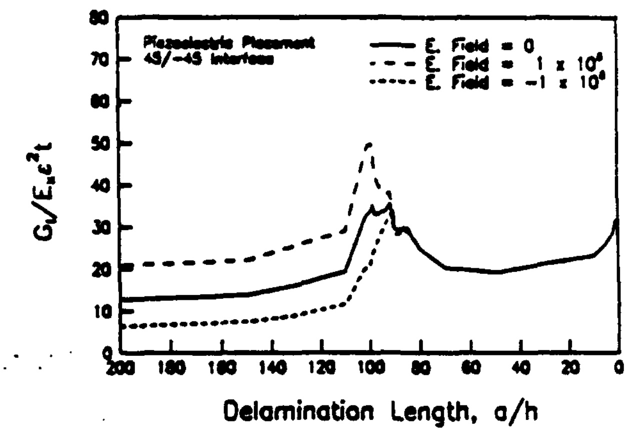

Figure 2. Mode I Strain energy release rate variation for varying delamination lengths when piezoelectric layer is in the 45/-45 interface.

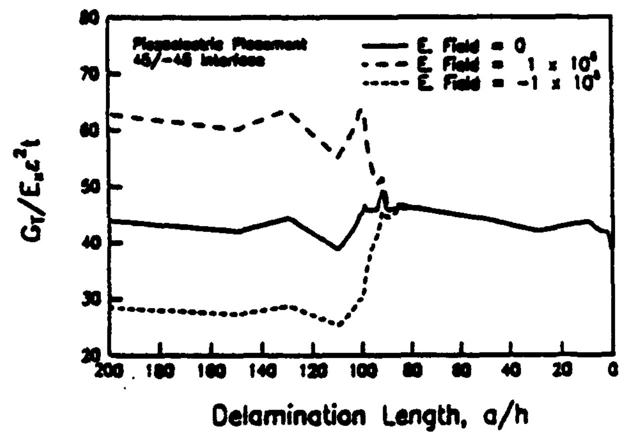

Figure 3. Total Strain energy release rate variation for varying delamination lengths when piezoelectric layer is in the 45/-45 interface.

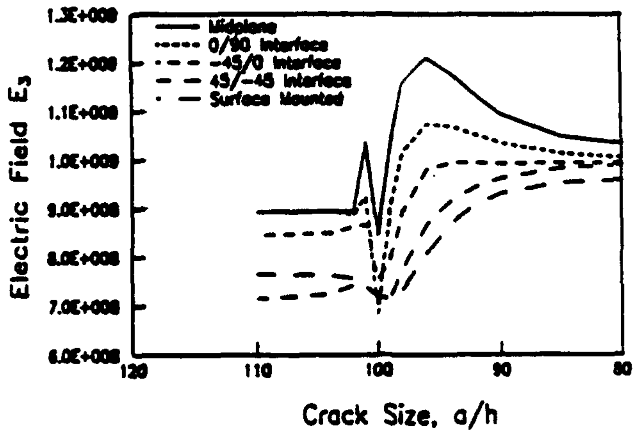

Figure 4. Electric response of the piezoelectric layer in different interfaces to delamination growth.

SPATIALLY SHAPED SELF-SENSING ORTHOGONAL PIEZOELECTRIC ACTUATORS

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ABSTRACT

A perfect sensor/actuator collocation usually provides a stable performance in closed–loop feedback controls. A self–sensing piezoelectric actuator is a single piece of piezoelectric device simultaneously used for both sensing and control. (The sensor signal is separated from the control signal by using a differential amplifier; this signal is then amplified and fed back to induce control actions.) Self–sensing piezoelectric actuators have been proposed in recent years. Dosch, Inman, and Garcia (1992) proposed a self–sensing piezoelectric actuator for collocated control of a cantilever beam. Anderson, Hagood, and Goodliffe (1992) presented an analytical modeling of the self–sensing actuator system, and studied its applications to beam and truss structures. Rectangular–shape piezoelectric devices attached near the fixed end were used in both studies.

It is known that the spatially distributed orthogonal sensors and actuators are sensitive to a mode or a group of natural modes (Tzou, 1993; Lee, 1992). Spatially distributed piezoelectric sensors and actuators were investigated in a number of recent studies, such as beams, plates, rings, shells, etc. (Lee and Moon, 1990; Lee, 1992; Anderson and Crawley, 1991; Collins, Miller, and von Flotow, 1991; Hubbard and Burke, 1992; Tzou and Fu, 1993a&b; Tzou and Tseng, 1990; Tzou, Zhong, and Natori, 1993; Tzou, 1993; Tzou, Zhong, and Hollkamp, 1994). Based on the modal orthogonality, a spatially shaped self–sensing orthogonal modal actuator is effective to only a single mode; consequently, each vibration mode can be independently controlled, *independent modal control*, while the feedback control system is kept simple. This paper is to investigate the sensing and control characteristics of self–sensing orthogonal modal actuators.

A generic orthogonal sensor/actuator theory is presented first, followed by an application to a Bernoulli–Euler beam. Spatially distributed orthogonal sensors/actuators are designed based on the modal strain functions. A physical model is fabricated and its self–sensing control effectiveness tested. A 40μm polymeric piezoelectric PVDF sheets are cut and laminated on a plexiglas beam. Surface electrodes are connected by either silver pastes or surgical wires. A self–sensing feedback control circuit is setup and tested.

Experimental results show that the orthogonal modal sensors are sensitive to their respective modes. Free and controlled (via the self–sensing feedback control circuit) time

histories are recorded and their modal damping ratios calculated. The calculated results suggest that the modal damping ratios were enhanced by 77.5% for the first mode and by 23.5% for the second mode. The convergence of modal responses is determined by the product of the modal damping and the modal frequency. Thus, the independent modal control of continua can be effectively achieved by using the spatially distributed self-sensing orthogonal piezoelectric actuators.

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(C/OrthScAct.Wp/Fibgl)

Active Damage Control - Concepts a d Developments

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Active damage control (ADC) is the term used to describe active control techniques for detecting and alleviating high stress concentrations and damage in structures. Sensing, actuation and control are all required to perform this task. Sensing involves the selection of the appropriate sensors and their correct integration, both spatially and locally (embedding versus bonding) into the structure. Actuation involves the same considerations but also strongly relies on appropriate and accurate modeling of actuator/structure interactions. The control function from the ADC perspective can simply be monitoring and signal processing of the information received from the sensor system or it can include the actual control effected through the actuators. Our research addresses each of these areas and the work being done in each of those areas is described below.

Damage Identification and Control: In the area of damage identification, we are investigating both model-based methods and those that do not rely on analytical models. In the area of model-based methods, a technique for determining the optimal excitations to locate delaminations in composite laminates is being developed. The first step in the effort concerns the detection of a single delamination in a composite beam. The approach optimizes the spatial distribution of harmonic excitation to maximize the difference between the damaged beam and a model of the undamaged beam. The technique is called anti-optimization because it seeks to make the analytical model of the undamaged structure disagree as much as possible with the experimental results. The approach has been validated by analytical simulation, and experimental validation is in progress.

For non model-based methods, we are investigating artificial neural networks (ANN) and inductive learning methods from artificial intelligence paradigms. To asses the learning ability of ANN to detect delaminations, we have performed experimental work with beams. The frequency response data obtained from a piezoelectric actuator/sensor pair bonded to a beam structure with delaminations were used to train an artificial neural network by backpropagation to identify the severity and presence of a delamination. The effectiveness of several different configurations of the network, like the number of hidden layers and the number of hidden neurons, and the classification of the severity of delamination, have been investigated. The neural network, after training on a limited number of training data, is able to distinguish between damaged and undamaged specimens. The work is now being extended to plates with multiple actuators and sensors.

In parallel with our ANN work, inductive learning methods which develop rule-based algorithms from an 'operational specification' or an unordered set of examples are also being investigated. Such rules indicate the effect of independent variables on dependent variables. Within the context of damage identification, it is the definition of the operational specification which becomes the direction of focus. Current work investigates the selection of both dependent variables (which must quantify the damage) and independent variables (data which should be easy to gather and process). Experiments using commercial inductive learning tools have been conducted to identify damage on a variety of simple structures, and continuing work extends into more realistic structures with the hopes of developing more complete and comprehensive rules.

Being developed in parallel with the damage identification methods are inductive techniques for damage control. Algorithms developed in the artificial intelligence community, which rely little upon *a priori* knowledge, are being extended within the context of vibration control as a precursor to control of damage effects. Such algorithms have appeal because of the obvious complexity of the structures to be investigated, the possibility of changing parameters with damage, and the potential to control non-linear systems. The Boxes algorithm, which selects control values to minimize a performance index (PI), has been used in both physical and numerical experiments; and has controlled both transient and steady state responses without the need for a system model. A variety of issues must be considered in conjunction with Boxes, including: selection of the PI, effects of inherent quantization of system state and control, and the increasing controller complexity with increasing system order.

Impact detection and improving impact resistance: To detect impact, an instrumented drop weight impact tester with specialized specimen clamps and a moving X-Y table is being built. This tester will allow for the testing of up to 14" x 26" plates and will have an electronics package that calculates the amount of energy absorbed by the specimen during the low-velocity impact event. With this design, more than one location on a plate, can easily be impacted without changing the boundary conditions of the plate. Once completed, it will be used to determine impact location and impact energy using PZT sensors as part of an artificial neural network. In the area of improving the impact damage resistance of composite materials, we are investigating the use of shape memory alloy hybrid composites. By embedding small amounts of fibrous SMA materials into brittle composite materials, greater composite impact damage toughness can be achieved. Impact strain energy is more readily absorbed by the high-strain-to-failure SMA materials than by the brittle host composites and is therefore not available to initiate damage in the host composite material. Experiments are underway to verify the analytical models for this behavior.

Active stress alleviation: A study of the potential of active stress reduction by strain actuation was conducted. The first part of the study was theoretical, and intended to probe the limits of the approach. It was found that the stress concentration factor could be reduced from 3 to 1.6 by applying strains to a region from the hole up to $1.5r$, where r is the radius of the hole. The second part of the study sought the effects of present technology limitations on the achievable reduction with piezoelectric actuators. We have found that the most important technology limitation was the free induced strain limit of the available actuator materials. This limitation reduces the achievable reduction to about 2.25. Also, it calls into question the utility of the approach as compared to passive approaches such as stiffening of the hole area. Experiments with piezoelectric actuators are in progress to determine the practical constraints on the utility of this technique.

Actuator/structure interaction modeling: The correct modeling of actuator/structure interactions provides information about the forces applied by the actuators to the structure, which is then used to compute structural response. To this end, a generic impedance-based model for the dynamic analysis of induced strain actuator-driven structures has been developed. This method provides the actuator applied force as a function of frequency and also provides information necessary to compute the power consumption of such coupled electro-mechanical systems based on total mass. This method can be applied to problems of shape and vibration control of helicopter rotor blades, as well as to ADC concepts.

CONTINUUM ELECTRO–MECHANICS OF OF IONIC POLYMERIC GELS AS ARTIFICIAL MUSCLES FOR ROBOTIC APPLICATIONS

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EXTENDED ABSTRACT

Intelligent material systems and structures have become important to some applications in defense and civilian sectors of the society (see Ahmad, Crowson, Rogers and Aizawa [1]). Accordingly, based on such materials, structures and their integration with appropriate sensors and actuators, novel applications, useful for defense and civilian programs, have emerged. Numerous examples may be cited as can be seen from key *reference articles such as* Ahmad, Crowson, Rogers and Aizawa [1], Anderson and Crowson [2] and Anderson, Crowson and Chandra [3]. Ionic polymeric gels or better known as artificial muscles, in the context of intelligent/smart materials, present a number of potentially useful possibilities for robotic, artificial muscles, large motion actuators, micro valves for drug delivery systems, highly maneuverable smart and adaptive structures and other smart material systems and structures applications.

Ionic polymeric gels are three–dimensional networks of cross–linked macromolecular polyelectrolytes that swell or shrink many times their initial volume in water on addition of alkali or acids, respectively. Furthermore, swelling and collapsing of these gels have been also been experimentally observed with the application of appropriate electric fields. Essentially an imposed electric field changes the ionic concentration of a solution by electrochemical activities and thus effectively changes the pH of such solutions containing such ionic polymeric gels. Thus, direct electrical and computer control of the expansion and contraction of such ionic polymeric gels appears to be possible for robotic, medical valves, drug delivery systems and other engineering applications. A continuum electro–mechanical theory is presented for the dynamic deformation of ionic polymeric gels in the presence of an imposed electric field. The proposed theory is based on some recent experimental results obtained in our laboratory for the deformation of ionic polymeric gels and in particular polyacrylic acid plus sodium acrylate cross–linked with bisacrylamide (PAAM). The proposed model takes into account the electro–osmosis, the electro–phoresis and ionic diffusion of various species. It further considers the spatial distributions of cations and anions within the gel network before and after the application of an electric field. The model will then derive exact expressions relating the deformation characteristics of the gel as a function of electric field strength or voltage gradient, gel dimensions and gel physical parameters such as diffusivities of cations D_{GM} and anions D_{GP}, elastic modulus E,

temperature T, charge concentration of cations, C_{GM}, charge concentration of anions, C_{GP}, resistance R_g and capacitance C_g of the gel.

Thus direct electrical and computer control of the expansion and contraction of these polymeric ionic gels is possible because ionic polymeric gels are electromechanical in nature. Because they can convert electrical and chemical energy to mechanical energy, they may become of particular importance to some unique applications in engineering and medical profession. Recently Segalman, Witkowski, Adolf and Shahinpoor [4], and Shahinpoor [5], [6] have presented a macroscopic theory for the dynamic deformation of ionic polymeric gels. The present theory is an extension and revision to the theories presented in [4], [5] and [6].

ACKNOWLEDGMENT

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Abstract

Torsional Actuation with Extension-Torsion Composite Coupling and a Magnetostrictive Actuator

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This paper presents a study on the concept of using composite tube extension-torsion coupling with a magnetostrictive actuator to create the twisting motion of the trailing edge flap on a helicopter rotor blade for the purpose of vibration control. The magnetostrictive actuator applies an axial force on the tube which results in its twisting due to structural coupling. This concept is especially suited for full-scale applications since the force level can be large and the twist induced in the tube increases with length. An analytical model of a thin-walled extension-torsion coupled composite tube with an applied axial force is developed based on Vlasov theory. The essence of this analysis is that two-dimensional stress and displacement fields associated with any shell segment of the tube are reduced to the generalized one-dimensional beam displacements and forces. Finally, an optimization technique is used to maximize the induced twist by treating both the ply angles and the number of plies as the design variables and actuator axial displacement as the constraint.

From the analysis, the tip induced twist in an extension-torsion coupled tube under axial force is obtained as

$$\phi_s = \frac{K_{15}}{K_{11}K_{55} - K_{15}^2} Fl \qquad (1)$$

where F is the applied force, l is the length of the composite tube, and K_{11}, K_{15}, and K_{55} are the extension, extension-torsion, and torsion stiffness coefficients respectively.

The basic design problem consists of determining the lay-up of the composite tube that best utilizes the prescribed force and displacement characteristics of the magnetostrictive actuator in order to generate torsional motion.

Three different composite materials, graphite-epoxy, kevlar-epoxy, and glass-epoxy, are examined. Kevlar-epoxy is chosen because it results in the maximum twist for a known applied force. Assuming constant length, diameter, and number of plies, the maximum induced twist occurs at a ply angle of approximately 30°. In order to include variations in the number of plies as well as ply angle across the thickness, an optimization study is undertaken using a software package called Design Optimization Tools (DOT).

In the DOT program, the objective function is the induced twist of the tube, while the design variables are the ply angles and number of plies respectively. Taking the results from the optimization program for maximum induced twist, and considering ease of fabrication a $[30]_s$ lay-up is selected for the composite tube.

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Next, the composite tube is fabricated using an autoclave molding technique. Kevlar-Epoxy unidirectional prepregs are laid-up on a split metal mold. A vacuum pump is used for further compacting of the layers. After laminating the desired number of plies, peel ply is wrapped to provide surface finish to the tube. The lay-up is cured in a microprocessor-controlled autoclave. The cure cycle given by the prepeg manufacturer is used. At the end of the cure, the lay-up is removed from the autoclave. Finally, the vacuum bag is removed and the tube is released from the mold.

In order to utilize the extension-torsion coupling properties of the composite tube, the magnetostrictive actuator must be attached to the tube in such a manner that both twist and axial strain are allowed. Figure 1 shows the schematic of the composite tube and actuator assembly. In this design, the two flanges are integrally connected to the ends of the composite tube by means of adhesive bonding. At the base of the actuator, an end piece is bolted to the flange and a separate bolt secures the actuator to the end piece, keeping the end rigidly constrained. At the tip of the magnetostrictive actuator (i.e. the push rod) an adapter with an end nut lengthens the push rod allowing for the addition of two thrust bearings and a plug. These bearings are essential to the design as they allow the plug to rotate freely when the magnetostrictive actuator applies an axial force to the system. Since the plug is bolted to the flange, the composite tube will twist as the plug rotates.

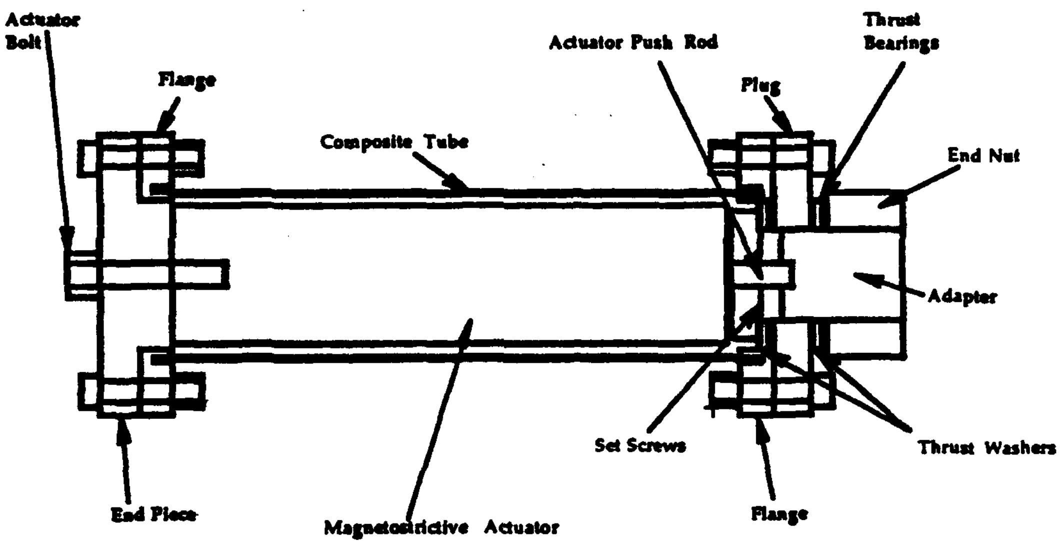

Figure 1: Schematic of composite tube and actuator assembly

Finally, the tip twist in the assembly will be measured using a mirror and laser system. *Analytical prediction will be correlated by experimental data. Subsequently,* the use of multiple actuators and longer tubes will be explored to obtain higher induced twist for a full-scale rotor system.

Magnetostrictive Mini Actuators For Smart Structure Applications

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Abstract

This paper investigates the feasibility of using magnetostrictive mini actuators (MMA) for smart structure applications, such as vibration suppression of beams. Based on electromechanical design principles, an energy efficient configuration of MMA is designed and fabricated. It primarily consists of two identical Terfenol-D rods (1mm square) driven by two coils in such a way that the magnetic field developed by two coils add up to make it energy efficient. The influence of geometry, material, and input current on the attainable strain and force is presented. In addition, the influence of these parameters on the overall size of MMA is discussed.

A magneto-thermoelastic model of the actuator is developed which includes a two dimensional thermal analysis. The thermal analysis addresses the effect of embedding the actuator in a host material. simulation results indicate the non-negligible thermal effects on the attainable strain. The thermal effects are shown to become predominant in actuators subjected to step input of driving current. Simulation also indicates that the thermal effects increase as the size of the actuator is reduced. Simulation of attainable strain and forces are conducted. The theoretical gain plot show that the actuator has relatively large frequency bandwidth.

Several special fixtures were used to characterize the MMA experimentally. The strain was measured using a high precision (0.1 micron resolution) capacitance sensor while the force was measured using a three-dimensional quartz force dynamometer. The driving current was obtained through a power amplifier developed in-house. The experimental strain and force data shows good agreement with the simulated result.

A cantilever beam, embedded with actuators, subjected to free vibration was chosen to study the feasibility of using MMA for smart structure applications. Based on Euler-Bernoulli's beam theory, a mathematical model of such a beam is developed. A simple control scheme was chosen to monitor and initiate control action as soon as the unwanted vibration of the beam begins. The minimum input energy criteria was selected due to the limitation on the maximum available input current. Simulation results show that it is possible to attenuate the vibration by properly choosing the input commands of excitation. The dynamic analysis results also provide a guide to selecting the control strategy and hardware selection. Further experimental verification is in progress.

Induced-Strain Actuation of Composite Beams and Rotor Blades With Embedded Piezoceramic Elements

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Introduction

Helicopters suffer from high vibration, which not affects ride quality, but reduces the life expectancy of the rotor components due to dynamic stresses. Passive vibration reduction devices in the form of isolators and absorbers are routinely used, but at a considerable weight penalty and restriction to a tuned operating flight condition. Active vibration reduction for helicopters is achieved through excitation of the blade pitch at higher harmonics of the rotational speed. This generates new airloads, which help to cancel out the original blade loads that cause vibration. Higher Harmonic Control (HHC) relies on multi-cyclic blade pitch control via swahplate actuation. In addition to an increase in power requirement at higher forward flight speeds, conventional HHC is limited to integral multiples of the number of blades. It is expected at a HHC system based on smart structures technology would overcome both these difficulties by reducing the overall weight of the control system and allowing for individual blade control (IBC) actuation at frequencies that are not limited to integral multiples of the number of blades. It is proposed to cause oscillatory lift on the blade through dynamic twisting with induced strain by distributed piezo actuators. For the suppression of vibratory hub loads, it is necessary to excite blade tip twist on the order of 1 to 2 degrees at frequencies of N, N (+/-) 1 per Rev (where N is the number of blades).

Previous research has introduced the uniform strain and Bernoulli-Euler theories to predict the static and dynamic bending and torsional response of anisotropic beams due to piezo-actuation. These models have been limited to surface-mounted and/or embedded piezoceramics which are oriented along the longitudinal axis of the beams. The focus of this research is to extend the uniform strain theory to predict both the torsional and bending responses of a beam with skewed embedded actuators. A one-*dimensional uniform strain beam* theory has been developed to include torsion. Since torsional actuation is inherently a two-dimensional phenomenon, analytical predictions will be validated with experimental results to assess the limitations of a one-dimensional formulation.

Analysis and Experiment

A one-dimensional uniform strain theory incorporating shear lag effects due to adhesive thickness has been developed to determine the twist and bending response of rectangular sandwich beams comprised of a rigid foam core, embedded crystal, shear layer and fiberglass skin (Fig 1). This theory is experimentally validated by test specimens varying in bond layer thicknesses, crystal axis orientation, and beam dimensions to provide data for a parametric study. The predicted bending and torsional response of one set of test specimens with a shear layer thickness of 0.020 inch and piezoceramics at various orientations is shown in Figure 2.

The simple beam theory will be modified to predict the torsional response of rotor blades with airfoil cross-sections. The results from these predictive studies will help to select important design variables in order to optimize the design of a smart blade.

The smart rotor model under development is a six-foot diameter, 1/8-th Froude scale, two-bladed hingeless rotor. The blade is constructed by laminating 10 mil pre-preg fiberglass cloth plies around a foam core *which is cured in a* NACA 0012 *airfoil mold* (Fig 3). The overall blade length is 26.58 inches from tip to root and the chord dimension is 3.0 inches. Specially-shaped 10 mil thickness piezoceramic elements are

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embedded below the fiberglass skin in banks of five discrete crystals at ply angles of [+/- 45] degrees on the top and bottom surfaces of the blade. Leads extend from each bank to the root of the blade, allowing independent actuation or sensing from each bank. A bending distribution along the span is achieved through 90-degree out-of-phase excitation of the top and bottom banks while an extension/twist distribution is achieved by in-phase excitation of the banks at equal potentials. The tip twist of the blade is first experimentally determined and then correlated with analytical predictions. The final smart rotor configuration will be tested on a hover stand and in the Glen L. Martin Wind Tunnel to measure the performance embedded actuators at various flight conditions.

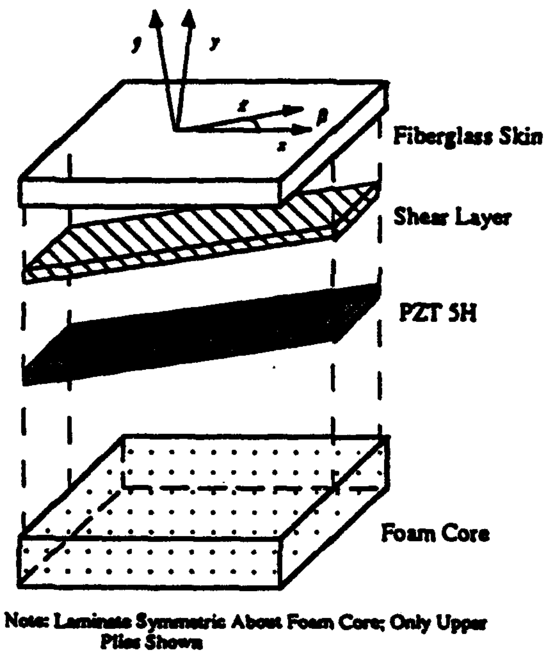

Figure 1. Laminate Lay-Up Sequence

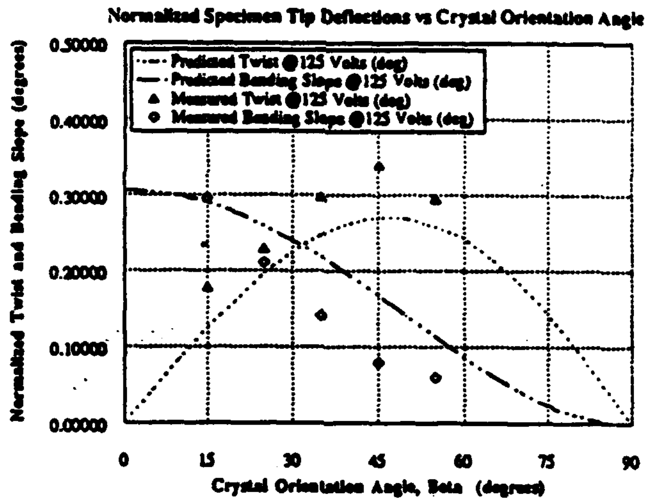

Figure 2. Normalized Specimen Tip Deflection With Embedded Piezoceramic Actuators at Various Orientation Angles

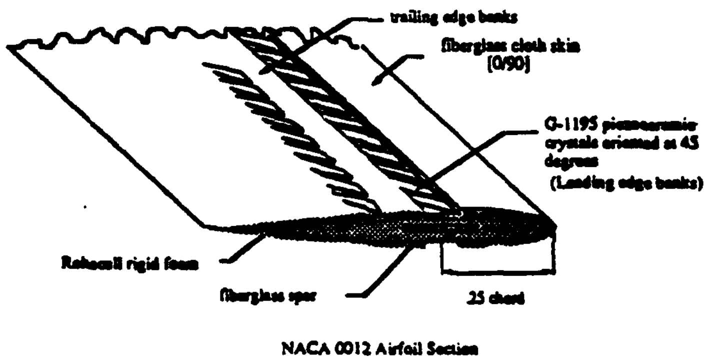

Figure 3. Piezoceramic Blade Cross Section Detail

Design, Fabrication, and Testing of a Scaled Rotor with Smart Trailing Edge Flaps

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Introduction

Because of the unsteady aerodynamic environment at the rotor disk, helicopter blades experience high levels of vibratory forces which are transmitted to the fuselage. The development of a Froude scale helicopter rotor model with trailing edge flap to actively reduce vibration, by directly altering the airloads on the blades, is carried out. It is envisioned that using a trailing edge flap driven by smart-materials actuators embedded in the blade with the necessary displacement and force characteristics can provide a lightweight, compact, vibration suppression system. Such a system can also provide an individual blade control (IBC) capability.

A six foot diameter rotor model was built using commercially available piezoceramic bimorphs to actuate the trailing edge flap. The bimorph actuator was cantilevered at the blade spar and the small bending deflection at the tip of the bimorph was amplified to drive the flap using a mechanical leverage arrangement. Hover test results proved that the bimorph flap actuation system works, but there was a decrease in the actuator authority with increased rotor RPM due to the increased dynamic pressure [Reference 1].

The objective of this research is to build an improved smart trailing edge flap to reduce vibration and then test the rotor model on the hover stand and in the Glenn L. Martin Wind Tunnel to evaluate its performance under different flight conditions.

Improving the Flap Actuation System

The flap actuation system, shown in Figure 1, is being improved by resizing the dimensions of the flap and the bimorph actuators. Using simple aerodynamic characteristics of a trailing edge flap [Reference 2], parametric studies are carried out to match the displacement and force characteristics of the actuator with the flap aerodynamic characteristics.

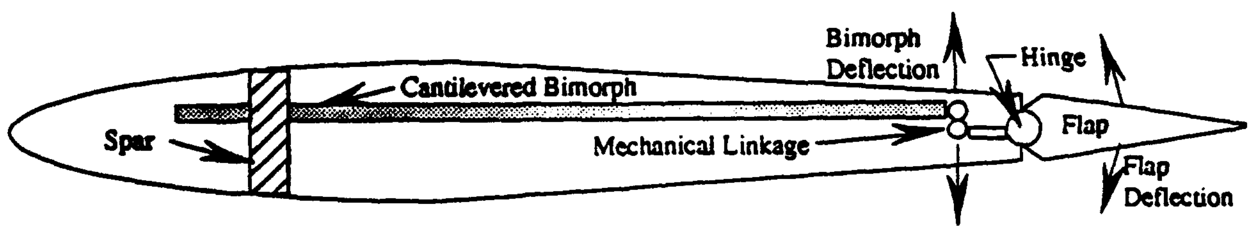

Figure 1. Cross Section of the Bimorph Flap Actuation System.

From the previous experimental rotor that used 2 layer bimorph actuators, it became clear that the actuators need to have higher force capability. Therefore, thicker 4 layer actuators with higher bending stiffness were built

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and tested under static loads. They showed much improved force capability, but lower displacements. The flap's linkage arm displacement and force requirements to obtain 5% flap authority (additional steady lift due to a flap deflection / total steady lift with zero flap deflection) at 8 degrees collective with a 20% flap chord was calculated for different flap spans. A comparison in Figure 2 between actuator capability and flap linkage arm requirements shows that the 4 layer actuator has better authority than the 2 layer actuator, however, the desired 5% flap authority can not be obtained with these actuators. Using this comparison scheme, a larger actuator is being designed to meet the desired flap authority.

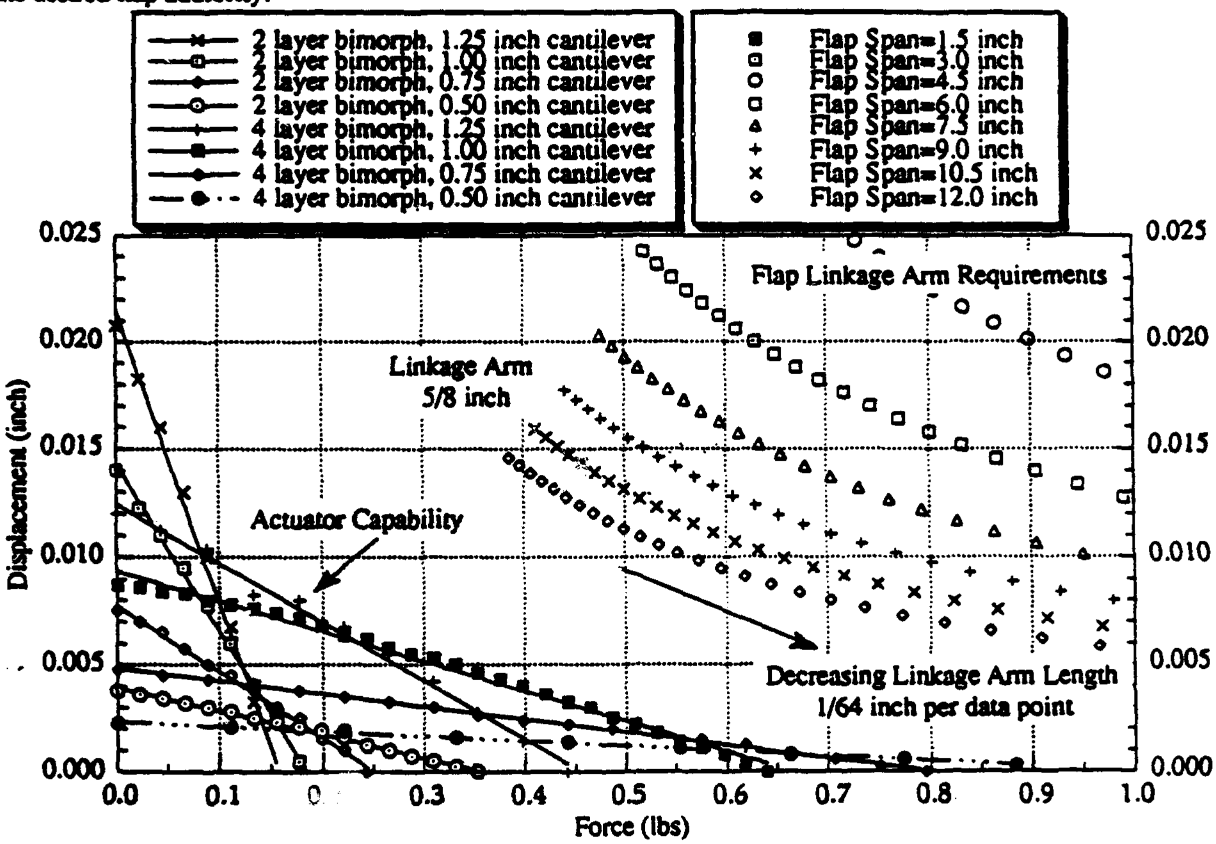

Figure 2. Comparison of Linkage Arm Requirements and Bimorph Actuator Capability.

Future Work

At the present time, a second experimental rotor with a longer span and multi-layered actuators is being built. The rotor will first be tested on the hover stand for a range of rotor speeds and collective settings. Eventually when the desired flap authority is obtained, testing of the rotor model will be carried out in the Glenn L. Martin Wind Tunnel and the flap performance will be evaluated at different flight conditions.

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Active and Semi-active Constrained Layer Damping

Keynote Speech by

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Smart Structures Application to Rotorcraft

Invited Presentation by

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PARAMETRIC CONTROL OF STRUCTURAL VIBRATIONS VIA ADAPTIVE MATERIALS

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ABSTRACT

Background

Structural vibration suppression via parametric control actions has been of popular interest in recent years. In such systems, the structural damping and stiffness characteristics are on-line varied according to feedback signals and control commands. These semi-active structures have the advantages of both the passive and active systems. They can adapt to system variations through feedback actions, and are thus more effective than passive structures. On the other hand, they normally require less power, are less sensitive to spillover, and are more stable than structures under fully-active actions. With the recent development of smart materials, on-line parameter variations could be physically achievable.

While the adaptable semi-active structure concept is promising, more research work is needed to realize this idea. Promising smart materials need to be identified, characterized and designed for semi-active applications. Integrated adaptive structures need to be synthesized and analyzed. Novel and robust parametric control algorithms need to be developed to take care of the unique characteristics of semi-active structures, such as their distributed nature and nonlinearity. The overall goals of this research are to address the above issues, gain fundamental understanding of the integrated systems, and create methodologies to maximize the controllability of the adaptive materials and optimize the semi-active structure performance.

Problem Statement

In general, semi-active structures can be categorized into two major categories: structures with adaptable energy dissipation/storage mechanisms, and structures with adaptable energy-exchange sub-systems. Possible actuator materials for the first type of semi-active structures include electrorheological fluids [Coulter et al. 1989; Duclos, 1988; Gandhiand Thompson, 1988; Wang et al., 1993] and piezoelectric materials [Kim and Jones, 1992]. Control laws for this group of structures have been investigated by various researchers [Habib and Radcliffe, 1991; Rhan and Mote, 1992; Kim and Wang, 1993; Wang et al., 1993].

For structures with energy-exchange sub-systems, the concept is to reduce the main structure vibration via a secondary external element. A classical example is the mechanical vibration absorber. Another possible type of actuators will be piezoelectric materials with shunted electrical circuits. The shunting circuit may include inductors as well as resistors [Hagood and von Flotow, 1991; Edberg and Bicos, 1991]. With this configuration, the coupling of a second order RLC electrical circuit with a second order structure gives rise to behavior analogous to that of vibration absorber systems. This passive approach can be extended to semi-active applications. In concept, this involves the use of a variable resistance as well as variable inductance in the circuit. Real-time control systems for this class of semi-active structures have not been studied extensively.

Objective and Issues

This paper is concerned with the development of a parametric control law for semi-active structures with adaptable sub-systems for on-line vibration suppressions. The major issues in controlling such systems are the nonlinearities due to state-dependent parameters and actuator constraints, and the balance between suppressing the main structure vibration versus stabilizing the sub-system dynamics.

Summary of Approach and Results

In this paper, an Energy-Based Variable Structure Control algorithm is presented. The main idea is to on-line vary the sub-system parameters and maximize the main structure energy reduction rate through output feedback. A Fuzzy Logic is designed to balance between the main structure energy and the sub-system energy. In other words, we are minimizing the structure vibration while constraining the sub-system motion.

The control law is tested using a beam example. The effectiveness of the Variable-Structure Fuzzy Control is investigated through computer simulations. An impulse response case was first used to examine the system's ability to return to its equilibria under transient disturbances. An external disturbance with time-varying frequency was then assumed to emulate an unbalanced rotor start-up scenario. It is shown in these cases that the parametric control system can reduce the structure energy level and vibration amplitude significantly.

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PIEZOTHERMOELASTIC RESPONSES AND CONTROL OF PIEZOELECTRIC LAMINATED STRUCTURES

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ABSTRACT

New active "intelligent" structural systems with integrated self–sensing, diagnosis, and control capabilities could lead to a new design dimension for the next generation high–performance structural and mechanical systems (Tzou & Anderson, 1992; Tzou & Fukuda, 1992). There are a number of active electromechanical materials, such as piezoelectrics, shape memory alloys, electrostrictive materials, electromagnetoelastic materials, electrorheological materials, etc., commonly used in active structural applications (Tzou & Anderson). Piezoelectrics are very popular in both sensor and actuator applications because their inherent electromechanical characteristics: *the direct and converse piezoelectric effects* (Tzou, 1993). Distributed sensing and control of continua using distributed piezoelectric transducers has been intensively studied in recent years. Distributed piezoelectric layers laminated on an elastic continuum can serve as distributed sensors via the *direct piezoelectric effect*. The layers can also be used for actuation and control, via the *converse piezoelectric effect*, when external high voltages are applied (Tzou & Fukuda, 1992; Crawley and deLuis, 1987).

It is known that variation of external temperature can significantly change the sensing and control effects of distributed piezoelectric transducers (Tzou and Howard, 1992; Tzou and Ye, 1993). However, this piezothermoelastic behavior of distributed piezoelectric transducers has not been investigated; this coupled elastic/electric/thermal behavior needs to be understood in order to effectively control the active piezoelectric structures. This paper is concerned with the piezothermoelasticity of distributed sensor/actuator and control of piezoelectric laminates exposed to a steady state temperature field.

Linear piezothermoelastic constitutive relations are defined first. A new 3–D piezothermoelastic thin finite element is formulated using the variational principle. Piezothermoelastic response and control of laminated piezoelectric structures are then derived. The governing equation shows the coupling of elastic, electric, and thermal fields. Thermally induced voltage generation of a distributed PZT layer laminated on a steel beam is investigated. It is observed that the voltage is contributed by two effects: 1) the pyroelectric effect and 2) the thermal strain effect.

Static deflection due to a thermal gradient between the top and bottom surfaces is calculated. Static and dynamic controls of a snap–back response are also investigated.

Analyses suggested that two voltages are required in order to fully control the oscillation in the thermal gradient environment. One voltage is used to compensate the thermally induced static deflection and the other voltage is used to control the dynamic oscillation.

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VIBRATION CONTROL OF ROTATING BEAMS WITH ACTIVE CONSTRAINED LAYER DAMPING

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ABSTRACT

The vibration of rotating beams are attenuated using a new class of Active Constrained Layer Damping (ACLD) treatment. The ACLD treatment consists of a visco-elastic damping layer which is sandwiched between two piezo-electric layers. The three-layer composite ACLD when bonded to the beam acts as a SMART constraining layer damping treatment with built-in sensing and actuation capabilities. With such capabilities the shear deformation of the visco-elastic damping layer can be controlled and actively tuned to the response of the rotating beam in order to enhance the energy dissipation mechanism and improve the vibration damping characteristics.

The dynamics of a rotating beam, treated fully or partially with ACLD treatments, are described with a finite element model. The model accounts for the interaction between the rotating beam, the piezo-electric sensor/actuator, the visco-elastic damping layer and an appropriate control law. The model provides means for predicting the damping characteristics of the ACLD at different rotational speeds, setting angles and controller gains. The theoretical predictions of the model are compared with the experimental performance of a beam partially treated with a Dyad 606 visco-elastic layer sandwiched between two layers of polyvinylidene fluoride (PVDF) piezo-electric films. Comparisons are also presented with the performance of conventional passive constrained layer damping. The results obtained clearly demonstrate the attenuation capabilities of the Actively-controlled Constrained Layer Damping and suggest its potential in suppressing the vibration of practical systems such as helicopter rotor blades.

1. INTRODUCTION

Considerable interest has been directed recently towards the development of various control systems to damp out the structural vibration of rotating beams [Cannon and Schmitz 1984], in general, and helicopter rotor blades [Strehlow and Rapp 1992, Nitzsche and Breitbach 1992a and 1992b] in particular. The emphasis in these studies has been placed on using either purely passive or purely active control systems. In the present study, the Active Constrained Layer Damping (ACLD) treatment [Baz 1992 and 1993, Baz and Ro 1993a, 1993b and 1993c] is considered in an attempt to combine the attractive attributes of both the passive and active controls to achieve optimal vibration damping. The ACLD provides an effective means for augmenting the simplicity and reliability of passive damping with the low weight and high efficiency of active controls to attain high damping characteristics over broad frequency bands. Such characteristics are particularly suitable for damping the vibration of critical systems such as rotorcraft blades where damping-to-weight ratio is very important.

This paper is organized in five sections. In section 1 a brief introduction is given. The concept of the active constrained layer damping is presented in section 2. The theory governing the operation of the ACLD treatment of rotating beams is developed in section 3. In section 4 the performance of the ACLD is presented and compared with those of conventional constrained layer damping. Section 5 gives a brief summary of the conclusions.

2. THE CONCEPT OF THE ACTIVE CONSTRAINED LAYER DAMPING

The proposed ACLD consists of a conventional passive constrained layer damping which is augmented with efficient active control means to control the strain of the constrained layer, in response to the structural vibrations as shown in Figure (1). The visco-elastic damping layer is sandwiched between two piezo-electric layers. The three-layer composite ACLD when bonded to the rotating beam acts as a SMART constraining layer damping treatment with built-in sensing and actuation capabilities. The sensing, as indicated by the sensor voltage V_s, is provided by the piezo-electric layer which is directly bonded to the beam surface. The actuation is generated by the other piezo-electric layer which acts as an active constraining layer that is activated by the control voltage V_c. With appropriate strain control, through proper manipulation of V_c, the shear deformation of the visco-elastic damping layer can be increased, the energy dissipation mechanism can be enhanced and the structural vibration can be damped out.

In this manner, the ACLD provides a practical means for controlling the vibration of massive structures with the currently available piezo-electric actuators without the need for excessively large actuation voltages. This is due to the fact that the ACLD properly utilizes the

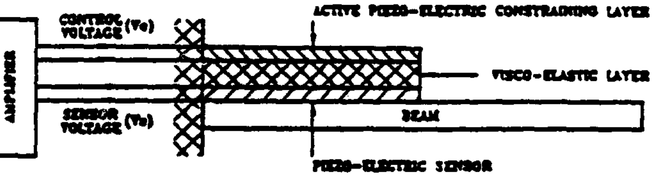

Figure (1) - Schematic drawing of the active constrained layer damping

piezo-electric actuator to control the shear in the soft visco-elastic core which is a task compatible with the low control authority capabilities of the currently available piezo-electric materials.

3. FINITE ELEMENT MODELING OF ROTATING BEAM WITH ACLD TREATMENT

The dynamics of rotating beams have been studied extensively (Hoa 1979, Putter and Manor 1978).

In the present study, a finite element model will be presented to model the dynamics of a rotating cantilevered beam of uniform cross section which is treated with an ACLD treatment. The beam under consideration has its mid-plane set at an angle θ to the plane of rotation to represent the setting angle (or the angle of attack).

The dynamics of the ith element of the beam are described by the following equation of motion:

$$[M_i]\ \{\ddot{\Delta}_i\} + [K_i]\ \{\Delta_i\} = \{Q_i\} \tag{1}$$

where $\{\Delta_i\}$, $\{\ddot{\Delta}_i\}$ and $\{Q_i\}$ denote the nodal deflection, acceleration and external load vectors respectively. The nodal deflection vector $\{\Delta_i\}$, of an element i bounded between nodes j and k, is = $\{u_{1j}, u_{3j}, u_{1k}, u_{3k}, w_j, w_j', w_k, w_k'\}^T$, with u_1 and u_3 denoting the axial deflection of the active constraining layer and beam/sensor system respectively. Also, w and w' denote the transverse deflection and slope respectively. The matrix $[M_i]$ defines the consistent mass matrix of the element and the matrix $[K_i]$ defines its stiffness as follows:

$$[K_i] = [K_{c1}] - [K_{c2}] + [K_b] + [K_e] + [K_G] + [K_p] \tag{2}$$

where $[K_{c1}]$ = the stiffness due to the in-plane centrifugal stresses σ_x.

$[K_{c2}]$ = the stiffness due to the out-of-plane centrifugal forces.

$[K_b]$ = the stiffness due to the flexural rigidity of the entire beam.

$[K_e]$ = the stiffness due to extension of the active constraining layer and beam / sensor system.

$[K_G]$ = the stiffness due to shearing of the visco-elastic layer.

and $[K_p]$ = the stiffness due to the active piezo-electric constraining layer.

4. PERFORMANCE OF A ROTATING BEAM WITH ACLD TREATMENT

4.1. EXPERIMENTAL SET-UP

Figure (2) shows a schematic layout of the experimental set up used in evaluating the performance of the ACLD treatment at different rotational speeds, setting angles and controller gains. The beam used in this study is anchored from one end to a rotating base driven by a variable speed DC motor. Table 1 lists the main physical, geometrical and dynamical properties of the beam.

The beam is treated with an Active Constrained Layer Damping (ACLD) which consists of a visco-elastic sheet

Table 1 - Main properties of the test beam

Length (cm)	Width (cm)	thickness (cm)	density (gm/cc)	Young's Mod. (GN/m^2)	1st Mode (Hz)
28.0	5.08	0.12	1.26	2.54	4.50

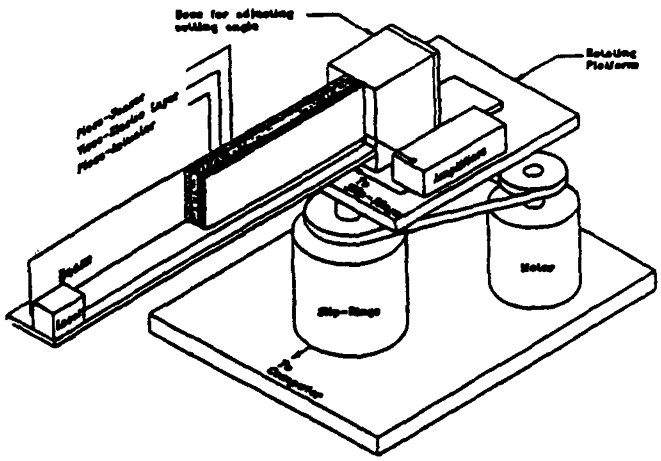

Figure (2) - Schematic drawing of the rotating beam experimental set-up

of DYAD-606 from SOUNDCOAT sandwiched between two piezo-electric layers from AMP, Inc. (Valley Forge, PA). The piezo-electric layers are made from PVDF polymeric films number SO28NAO. Table 2 lists also the physical and geometrical parameters of the visco-elastic and piezo-electric layers.

Table 2 - Physical and geometrical properties of ACLD

Layer	Length (mm)	Thickness (mm)	Density (kg/m^3)	Modulus (Mpa)
Visco-elastic	140	0.254	1104	20**
Piezo-electric	140	0.711	1800	2250*

* Young's modulus ** shear modulus

The signal from the piezo-electric sensor and the signal to the piezo-electric constraining layer are transmitted to/from the rotating platform via a ten-ring slip ring arrangement from Airflyte Electronics (model CAY-125-10-1). Also a laser sensor (Model MQ - Aeromat Corp., Providence, NJ) is placed on the rotating platform facing the beam free end to provide means for calibrating the piezo-sensor. The laser sensor has an accuracy of 20 μm over a frequency band between 0-1000 Hz.

The piezo-sensor signal is fed into an analog power amplifier (Model AM-5 from Wilcoxon Research, Rockville, MD) and the amplified signal is fed back, through the slip rings, to the piezo-constraining layer. The control action is, accordingly, just a simple analog proportional action.

4.2. EXPERIMENTAL RESULTS

Figure (3) shows the effect of varying the controller gain on the frequency spectrum of the amplitude of vibration of the rotating beam when Ω = 1.889 Hz and the setting angle θ = 30°. Significant attenuation of the vibration is observed as the gain is increased. It is evident also that first natural frequency of the beam increases with increased gains. Displayed also in Figure (3), for the sake of comparison, is the uncontrolled characteristics when the ACLD is unactivated (i.e. K_p=0) which corresponds to the case of Passive Constrained Layer Damping (PCLD). The results obtained indicate that the ACLD treatment, with gain of 300, reduces the amplitude of vibration to half that with the PCLD treatment.

Figures (4-a), (4-b) and (4-c) show comparisons between the amplitude of vibration with the ACLD and PCLD for setting angles of 30, 60 and 90° respectively. The results displayed correspond to Ω = 1.889 Hz and controller gain K_p = 300. The figures emphasize the effectiveness of the ACLD treatment as compared to the conventional PCLD. Furthermore, the effectiveness of the ACLD is maintained over a wide range of θ even with constant controller gain.

4.3. COMPARISONS BETWEEN THEORY AND EXPERIMENTS

The predictions of the natural frequency of the rotating beam at different rotating speeds and setting angles and controller gain, as obtained from the solution of the eigenvalues of equation (1), are compared with the experimental results as shown in Table 3. Close agreement is evident between the theoretical predictions and the experimental results.

5. CONCLUSIONS

This paper has presented a *new* class of active constrained layer damping treatment for attenuating the vibration of rotating beams. The treatment consists of

Table 3 - Comparisons between experimental and theoretical natural frequencies

Angle θ (°)	Speed Ω (Hz)	Gain K_p	Exp. Freq. ω_n(Hz)	Theo. Freq. ω_n(Hz)
90	0	0	4.500	4.503
	1.333	0	4.598	4.608
	1.889	0	4.700	4.710
	1.889	300	4.905	4.978
60	1.889	0	4.800	4.720
	1.889	300	5.098	4.986
30	1.889	0	4.850	4.735
	1.889	150	5.000	4.870
	1.889	225	5.208	4.940
	1.889	300	5.348	5.002

conventional visco-elastic core augmented with built-in sensing and actuation capabilities. The equations governing the performance of this class of surface treatment are presented using a finite element formulation. The validity of the model is checked against experimental results. The effectiveness of the ACLD treatment as compared to PCLD treatments is demonstrated experimentally at different operating conditions. The results obtained suggest the potential, simplicity and practicality of the ACLD treatment. It

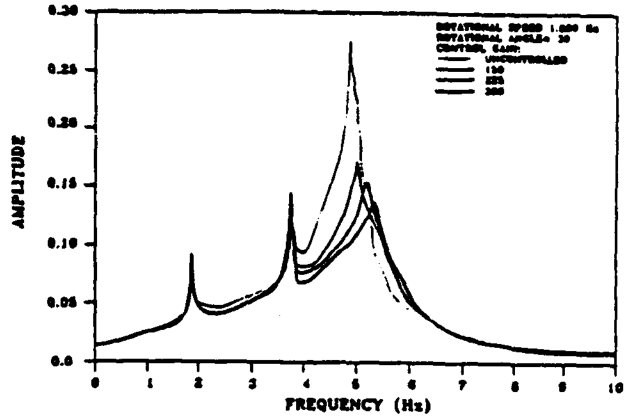

Figure (3) - Effect of controller gain on amplitude of vibration of beam.

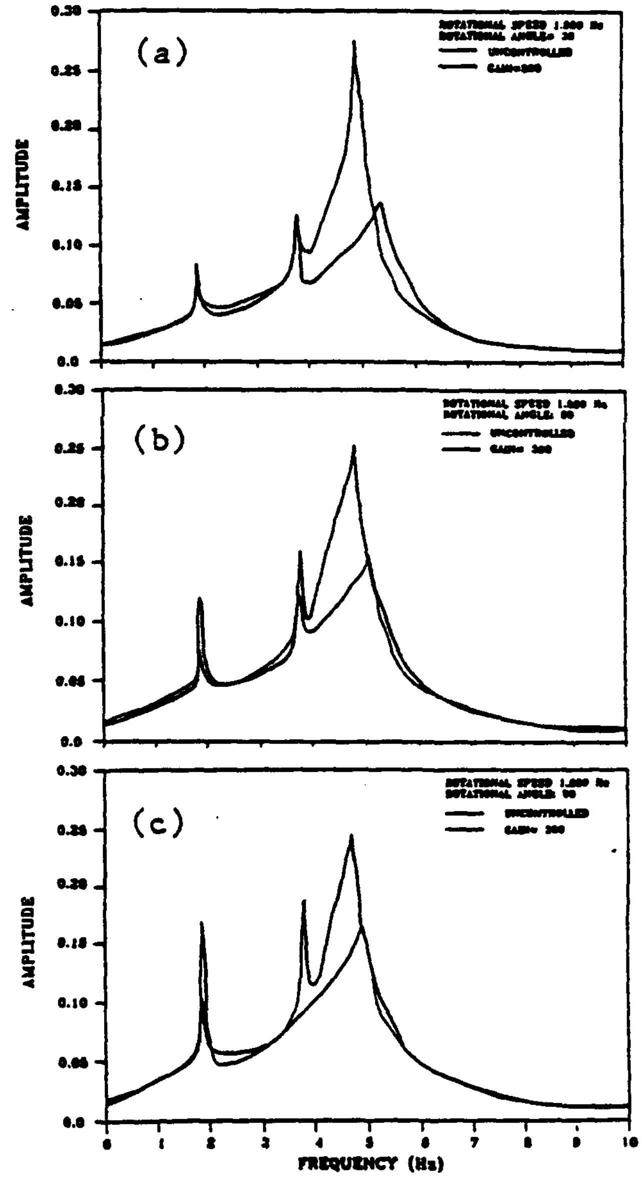

Figure (4) - Comparison between ACLD and PCLD at different setting angles

is found also that the performance of the ACLD with a proportional controller is very effective in attenuating the induced vibration.

It is important here to note that the emphasis of the present study has been placed on the demonstrating the feasibility of the ACLD treatment. Extension of the work to include optimal placement and sizing of the ACLD treatment, selection of the optimal control gains, and optimizing the shape of the piezo-sensor/actuator pairs are among the important issues that are currently under consideration to enhance the effectiveness of the ACLD treatment.

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APPLICATION OF MULTI-CHANNEL DESIGN METHODS FOR VIBRATION CONTROL OF AN ACTIVE STRUCTURE

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ABSTRACT

Active control methods have great potential for suppressing vibrations in flexible structures. The objective of these methods is to suppress the transmission of vibrations in the structure in order to avoid structural damage or to reduce undesired structurally radiated noise. The use of piezoelectric actuators and sensors bonded to a flexible structure is an attractive way to address the vibration suppression problem due to their light weight, high force, and low-power-consumption capabilities. In conjunction with appropriate control architecture techniques, the active structure is designed to modify its dynamic response to reduce vibration by changing its dynamic properties, such as damping, and its propagation and disturbance rejection characteristics.

Vibratory disturbances originating from rotating machinery usually consist of sinusoidal components which are transmitted to the supporting structure. To obtain effective vibration minimization, it is advantageous to cancel vibrations at multiple locations on the structure. When distributed pieozoelectric sensors and actuators are bonded in collocated or non-collocated positions, multi-input, multi-output control issues of stability, sensitivity, and robustness become essential in the control architecture formulations. This paper presents multi-channel control methods for actively controlling vibration transmission of narrow-

Vibration Suppression Using Programmable Structures

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Abstract

A programmable structure is a form of a smart material system consisting of a structure with imbedded self sensing actuator and a surface mounted, self contained, feedback control circuit. The control circuit is programmable in as much as the control gains can be adjusted after the electronics have been mounted on the structure. The only external device has been tested and its physical parameter determined. The results reported here examining modeling and control details based on these experimentally determined parameters.

The closed loop performance of this programmable structure is examined by comparing the response of the structure under various different control schemes. These responses are compared to a baseline structure with no control as well as a similarly configured beam with constrained layer damping. The smart structure approach yields an order of magnitude increase in performance over an open loop configuration with only structural damping.

Smart Structures: Control Designs and Their Experimental Validation

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Abstract

Due to earth-based and space-based applications, and with the promised advent of light-weight high-strength composite materials, much attention has been given to modeling and control of large flexible structures and weapon pointing systems. Another class of systems, for which vibration suppression is of great importance, is high speed positioning devices such as probes for electronic circuit boards, robotic manipulators, and machine tools. Utilization of smart or intelligent materials in control of systems exhibiting flexibility is receiving increased attention recently. Several experimental setups and control designs for flexible multi-body systems and structures with piezoelectric ceramics as sensors and actuators have been and are being developed at the Control/Robotics Research Laboratory (CRRL). The emphasis of the experimental research in CRRL is on control of flexible mechanical structures, smart structures, and robotic systems. Control objectives for these experiments range form nonlinear controllers to fuzzy logic and neural network control systems for active vibration suppression to slewing and pointing, and combinations thereof. Furthermore, system and parameter identification for control is another primary objective in the development and utilization of these experiments.

band disturbances in a typical finite beam structure bonded with piezoelectric sensors and actuators. The active structure is modelled using finite element analysis and experimental discrete modal summation methods. PZT sensors and actuators are located in collocated pairs and positioned to ensure effective modal coupling. The moment-curvature relationship is used to determine the placement of the piezoelectric materials at locations where the strain and moment contributions will be optimal for both sensing and actuation.

The control architecture is geared towards disturbance rejection and enhanced performance while maintaining robustness to the active structure plant variations and modeling uncertainties. The methods investigated include one based on direct, constant-linear-gain rate and stiffness control, while another is based on the Linear Quadratic Gaussian/Loop Transfer Recovery method with augmented states to obtain disturbance accommodation. An H_∞ optimization control scheme and an adaptive feedforward multi-channel control algorithm based on the least-mean-square algorithm are also presented. The effectiveness of the control schemes is being evaluated and the advantages and disadvantages in their application discussed. A hybrid multi-channel control formulation based on an evaluation of the above control methods is being developed to account for both steady-state and transient vibrations. The hybrid controller essentially combines the faster response characteristics of a robust feedback law together with a robust feedforward adaptive algorithm. Results from the application of the control strategies to obtain vibration minimization of narrow-band disturbances in the active structure are presented. Recommendations for further research and applications based on an evaluation of results are also discussed.

Control Issues in Smart Structures*

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Structural vibration is either due to 1) persistently exciting (broad band) disturbances like random disturbance inputs or occasional wind gusts (step disturbance inputs) and/or 2) single/multiple frequency inputs, e.g. helicopter rotor blades being disturbed mainly with the frequency of 4/rev and automobile body panels vibrations due to engine vibrating at the firing frequency and its higher order harmonics. Sometimes both kinds of disturbance inputs act on a structure, e.g. the automobile body panels that in addition to engine caused vibration are also subject to the random disturbance inputs from the road.

The common sense approach to vibration control of structures subject to broad band disturbances is increasing the damping (passively or actively). Depending on the sensing mechanism and the proximity of sensors and actuators in active structures a few successful active damping schemes are proposed by researchers. They are all based on the addition of around +90 degree phase shift to the open loop system at the natural frequencies of the modes designated to be damped. For example having strain or displacement as the measured output, with collocated or nearly collocated arrangements, feedback of the strain rate (a differentiator in the numerator, which mimics the attributes of a dashpot and is the principal damping mechanism) accompanied by a low pass filter (a 2nd or higher order system in the denominator) has proved to be very effective in adding local damping to the structure. The low pass filter is for filtering the high frequency measurement noise. The corner frequency of this controller, which is a simple lead compensator, is placed beyond the natural frequencies of the modes to be damped. Although it adds negative damping at high frequencies, due to its contribution of -90 degree phase shift to the open loop system, the controller has been employed effectively in smart structures actuated by piezoelectric plates. Another method of active damping mechanism is based on positive feedback of the integral of displacement or strain (known as the positive position feedback, PPF). This technique mimics the attributes of a passive tuned mass damper. The positive position feedback controller, which is an electronic or digital 2nd. order low-pass filter, is tuned to resonate at the structural natural frequencies and thus add a +90 degree phase shift (adding damping) at those frequencies. Similar to tuned mass dampers, at low frequencies this controller adds flexibility and at high frequencies it adds stiffness to the structure. Moreover it also tends to split the modes.

The active local damping, which considering the hardware limitations, would only lower the magnitude of the amplitude ratio at natural frequency(ies) of the structure. This phenomenon although very effective for broad band disturbance rejection, may or may not work when the disturbance is at certain frequency(ies). This is because those frequencies are not necessarily close to the natural frequencies of the damped modes. The matters become more complicated when the dynamics of the system and/or the frequencies of the disturbances are time varying, e.g. in helicopter rotor blades where the natural frequencies, as well as the disturbance frequencies, of the blade changes with the rotational speed of the rotor. And more importantly, active local damping schemes described above are based on collocated or nearly-collocated arrangement of sensors and actuators, which may not always be possible or desirable in every application. Although for single input single output structures with non-collocated sensor-actuator arrangement, classical control lead compensation technique could be used for damping the vibration.

* Due to the generality of the subject and space limitations, the references are omitted.

Positive position feedback controllers could be tuned such that the natural frequency of the compensator (filter) correspond to the excitation frequencies, rather than natural frequencies of the structure, and thus provide effective vibration cancellation. Another technique suitable for canceling the single or multiple frequency vibration is based on adaptive filtering schemes. In these schemes feedforward controllers with feedback adaptation are used. The adaptation speed in these schemes are very fast when the sampling frequency of the measured output is 4 times or higher even-integer multiples of the disturbance frequency(ies); this sampling technique is called synchronous sampling. The premise of this scheme is identifying the dynamics of the structure only at the frequency(ies) where excitation(s) are disturbing the system. Using synchronous sampling the plant could be represented by a low (as low as 2nd) order finite impulse response (FIR) filter, which makes the adaptation fast. Although the feedforward nature of the controller is attractive considering the stability concerns, but the adaptation is based on feedback schemes which makes the system vulnerable, like any other feedback system, to stability issues.

The controllers described above are reasonably straightforward to synthesize without needing an accurate model for the structure. Although simple and effective, they are not optimal controllers. The last three decades have brought major developments in the mathematical theory of multivariable feedback systems which include the state space concept for system description and the notion of mathematical optimization for controller synthesis. Various time-domain-based analytical and computational tools have been made possible by these ideas resulting in controller design techniques such as LQR and LQG methods, which their applications to structural control have been studied by researchers. The theory has increasingly concentrated on analytical issues and has not placed enough emphasis on issues which are important and interesting from the perspective of practical design and application. In particular the problem of model uncertainties had been somehow neglected by these theories.

Successful application of most optimal control techniques such as LQG controllers relies on the existence of an accurate model in the design stage. Considering the facts of 1) most smart structures, due to their considerable flexibility, require a high order model, and 2) the complexity of formulating their vibration due to having several degrees of bending and twisting, accurate modeling of these smart structures is rather complicated. More recently developed H_∞ and mu control methods allow the design of control laws that are robust against certain mathematically defined set of modeling uncertainties and have been successfully applied to controlled flexible structures and are viable techniques for the smart structures control. Their applications to smart structures, has also been studied with very promising results in terms of performance and stability robustness.

Basic goal in H_∞ control is reducing the infinity norm of the transfer function matrix mapping the exogenous input (including the disturbances) to the desired output, below 1. In most cases the disturbance input and the desired output could be scaled in the synthesis stage of the controller such that reduction of the infinity norm of the above-mentioned transfer function results in satisfactory performance. For example if only damping of certain number of lower modes is the objective of the closed loop control, then the scaling function (normally a low pass filter) on the desired output is selected in such a way that magnitudes of the peaks of the frequency response of the structure corresponding to those modes are reduced. On the other hands if vibration cancellation at one or multiple frequencies is the objective of feedback control, notch or comb filters can be used for scaling. In the event when both broad band and single/multiple frequency disturbance rejection is needed, the scaling function comprising of the combination of the two filters (low pass and notch) could be used, effectively and conveniently.

In summary, the sub-optimal control techniques such as strain/displacement rate feedback or positive displacement feedback are simple and yet very effective for adding local damping to smart structures. The optimal control techniques, e.g. H_∞ methods, although are more complicated to synthesize but offer flexibility for 1)adding damping to the structure without needing the collocated sensor/actuator arrangement and 2)cancellation of single/multiple frequency vibration.

DYNAMIC CHARACTERISTICS OF SPATIAL PIEZOELECTRIC SENSOR FILTERS

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ABSTRACT

Distributed piezoelectric sensors and actuators are increasingly used in many active structures (Tzou and Anderson, 1992) and precision electromechanical systems (Tzou and Fukuda, 1992). Unlike conventional discrete sensors and actuators, these distributed devices are usually responsive to spatially distributed phenomena; they are effective to sensing and control of multiple modes of distributed parameter systems – continua (Tzou, 1993). There are significant activities toward new research and development of piezoelectric devices in recent years (Baz and Poh, 1988; Hubbard and Burke, 1992, Lee and Moon, 1990; Birman, 1992; Tzou, et al. 1993; Tzou and Fu, 1993). However, detailed electromechanics and spatial filtering characteristics are not well understood. This paper is intended to clarify the sensing behavior of various spatially distributed piezoelectric sensors.

Spatial filtering characteristics of distributed piezoelectric sensors are discussed; three spatial filtering phenomena are investigated in this paper. In general, these filtering characteristics can be divided into three categories depending on: 1) sensor placement, 2) signal average, and 3) sensor shaping. Depending on the placement of the distributed sensor and induced strains, there are *bending sensors* and *membrane sensors*. Due to signal averaging on the surface electrode, sensor signals from different strain regions can be canceled out and result in a zero or minimum output, e.g., anti–symmetrical modes of a symmetrical structure. To overcome this problem, a distributed sensor can be spatially shaped to be sensitive to a mode or a group of modes.

As to demonstrate the classification, distributed sensors laminated on a cylindrical shell are proposed and their spatial distributed filtering characteristics investigated. It is noted that the fully distributed sensor is only sensitive to odd modes and insensitive to even modes, due to the signal cancellation of modal anti–symmetry. A distributed line sensor is studied and it is observed that the line sensor is only sensitive to all m = n modes. The transverse sensitivities of these two sensors are also studied. Analysis results suggest that the sensitivity increases when the sensor and the shell become thicker. The latter is due to an increase of bending strains in the sensor layers.

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Investigation of photoconductive semiconductors as reconfigurable electromagnetic sensors

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ABSTRACT

Today's airborne surveillance platforms have fully exploited the available sensing area with state-of-the-art technology. The capacity of these existing systems could be further extended by a reconfigurable electromagnetic sensor whose size, shape, and polarization can be modified dynamically. A structurally embedded reconfigurable antenna is also a desirable component for the future generation of "Smart Skin" military aircraft. To date most proposed reconfigurable antenna concepts have used a mesh of conducting elements connected by electronic/optoelectronic switches with the on-off pattern of the switches defining the size and/or shape of the antenna. An alternative approach for realizing a reconfigurable sensor is to exploit the photoconductive effect in various semiconductor materials. This presentation will briefly review the theory of photoconductivity in semiconductors and then describe a proof-of-concept photosensor experiment performed here at The University of Texas at Arlington.